An examination of sequential self-control task performance and why a temporary deterioration occurs over time; do motivation and glucose play a role?

By

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Declaration

I declare that the thesis is my own work, and has not been submitted in substantially the same form for the award of a higher degree elsewhere.

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Signature

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Date

Abstract

The research within this thesis focused on examining the concept of self-control; the ability of regulating and/or controlling responses, e.g. choosing a fruit salad rather than a more tempting chocolate cake. Self-control was of interest as evidence has repeatedly observed that the ability to apply self-control continually over time poses difficulty. Namely, when faced with completing two sequential tasks that both require self-control, typically prior research reported that the first task is completed successfully but there is a temporary impairment in self-control performance in the second. The work in this thesis attempted to address why a temporary deterioration in self-control performance occurs. Specifically, we drew on the strength model, which posits that self-control is directly fuelled by a limited resource that gets depleted when initially applied, leaving limited resources available for the second task. Glucose was proposed – though with recent debate - as the physiological resource and consequently we assessed the role of glucose in sequential self-control task performance. In addition evidence suggested that rather than self-control deterioration stemming from resource depletion, it is connected to a reluctance to allocate resources based on a lowering in intrinsic motivation. The seven studies that were conducted attempted to further examine and add to the debate about the factors that play a role in self-control depletion following prior exertion, with a specific focus on the effects of glucose and intrinsic motivation. Overall the findings from the studies somewhat challenge the direct role of glucose: no relationship between glucose and sequential self-control performance was observed. Intrinsic motivation was however predicted to be a stronger predictor of self-control ability over time, suggesting that perhaps the temporary deterioration in self-control performance is one of resource allocation rather than depletion. More research is needed to corroborate these findings but the accumulation of evidence within this thesis - added to the current research - supports more of the recent literature i.e. motivation plays an important role in successful self-control exertion.

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Paper four: Completing two consecutive self-control tasks successfully: does prior fasting duration modulate any glucose effects or does motivation play a role?

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Paper six: Sequential self-control task performance: the role of both motivation and age

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Paper seven: The relationship between motivation and self-control: does manipulating task interest restore a temporary impairment in self-control following prior exertion?

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Through signing this Statement, the supervisor agrees that:
a) the student's contribution to all the papers above is correct;
b) the student can incorporate these papers within the thesis;
c) the contributions of all the co-authors for each paper equals to 100% minus the involvement of the student.

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Exploring why a temporary deficiency in self-control ability appears to occur following prior exertion: An introduction

Background

Self-control is the ability we have to override a dominant response for another such as refraining from checking Facebook while at work, suppressing certain emotions in public (Baumeister, Vohs & Tice, 2007). Self-control is effortful and cognitively demanding. It is an executive function along with working memory and planning (Diamond, 2013), which are cognitive abilities involved in the top down processing of information; hence self-control is a high level cognitive skill. Self-control is applied widely in everyday life and used frequently (Hoffman, Baumeister, Foerster, & Vohs, 2012). Despite its regular use, the ability to apply self-control can weaken from time to time and self-control failure can occur. On a societal level this is demonstrated when we consider the issues that are associated with poor self-control such as crime, obesity, smoking and drug abuse (Baumeister, 2012). On a more general level however there is evidence to show that self-control can deteriorate in a short space of time. For example research showed that completing two tasks that require self-control in a sequential order led to participants performing well in the first task but displaying a temporary impairment in performance in the second task, with this being demonstrated widely across many studies (Hagger, Wood, Stiff, & Chatzisarantis, 2010); it thus appears to be quite a robust and consistent finding.

In an attempt to understand why a temporary deterioration in self-control performance occurs following prior exertion, early research was informed by an influential theory within the field known as the resource depletion/strength model of self-control (Baumeister, et al., 2007). This theory posits that a reduction in self-control performance stems from a decrease in the availability of a limited energy resource. When self-control is applied this energy resource gets drained, which results in there not being enough for the successful application of self-control in a subsequent task. Thus any impairment in self-control stems from the limited resources that are available to fuel successful performance.

One proposal was that this resource was glucose (Gailliot et al., 2007) with findings showing that peripheral levels of blood glucose significantly reduced following the completion of a cognitively demanding task (Fairclough & Houston, 2004; Gailliot et al., 2007) and glucose (relative to placebo) administration led to an improvement in performance in a later task of self-control (Gailliot et al., 2007; Masicampo & Baumeister, 2008; DeWall, Baumeister, Gailliot & Maner, 2008). This evidence however was later challenged (Kurzban, 2010) with findings failing to replicate i) a fall in peripheral blood glucose levels following self-control exertion (Molden et al., 2012; Dang, 2016) and ii) ability to maintain performance by mouth rinse with glucose solution, suggesting that metabolic digestion of glucose was not necessary for self-control ability to be restored (Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012).

More recent research has suggested that motivation might be a key factor involved in self-control performance. Extrinsic motivation refers to motivation that is directed by external rewards or incentives such as money (Ryan & Deci, 2000) and has been found to have an ameliorating effect on a temporary deficiency in self-control following prior exertion (Muraven & Slessareva, 2003). Motivation on an intrinsic level has also been shown to have restorative effects on self-control depletion (Muraven & Slessareva, 2003). Intrinsic motivation refers to the motivation we have to engage in something such as an activity task because of its' inherent interest or enjoyment (Ryan & Deci, 2000). The work conducted as part of this thesis was particularly focused on evaluating the effects of intrinsic motivation on self-control performance as this fitted more consistently with recent evidence as well as the theories that appeared after Baumeister et al.'s (2007) strength model of self-control.

For example the resource allocation account (Beedie & Lane, 2012) posits that a temporary reduction in self-control performance stems not from resource depletion but from an averseness to allocate resources to a task based on a lowering in motivation level. Those who perform well across two subsequent self-control tasks have the motivation to apply resources to both tasks leading to successful performance, with this motivation being driven by the level of interest and importance they attach to the tasks and also how enjoyable they consider them to be.

The shifting priorities account (Inzlicht & Schmeichel, 2012; Inzlicht & Schmeicel, 2016) takes a similar perspective but does not include the idea of a resource that might be limited. Instead they suggest that a temporary deterioration in self-control across two tasks stems from a shift in pattern of attention based on motivation level. Individuals only perform both tasks well if they consider them both to be personally relevant and enjoyable.

Thus there appears to be much debate and a wealth of mixed evidence on the study of sequential self-control performance and why failure arises. Recent evidence suggests that the initial resource depletion theory might be insufficient to explain the findings. The failure to consistently observe such temporary deterioration in self-control performance suggests the existence of other moderating or mediating factors. Although glucose was argued for a while to be a key fuel for successful self-control performance (Gailliot et al., 2007), recent evidence has challenged this (Dang, 2016) and further investigations are required. In addition the role of motivation in self-control performance needs to be examined further. The work described in this thesis aimed to further explore the role of glucose and motivation on self-control performance.

In summary, whether self-control deteriorates over time along with the factors that might be responsible for this has been a widely studied and is a very topical research area. The approach taken across all seven individual experiments reported in this thesis was to examine in more detail the potential factors that influence sequential self-control task performance and why typically a temporary deterioration in self-control performance appears to occur over time in the second task, with a particular focus on the role of both glucose and motivation.

Further, each study/paper within this thesis adopted a sequential two self-control task depletion paradigm, which has been the typical and widely employed methodological procedure that previous studies have used to examine self-control ability over time (Hagger et al., 2010). This ensured that the research conducted was consistent with prior research and could thus be more comparable.

Rationale for alternative format

The studies in this thesis (chapters three to nine) are written in paper format with two of these having already been published (paper one in PLOS one and paper five in Psychophysiology). The remaining papers are in ‘draft ready for submission’ format. Given the nature of the studies conducted and the series of interesting results they provided it felt appropriate to implement the alternative format structure for this thesis. Although they are all separate papers they do follow a coherent story – in terms of the consistent effects of motivation on sequential self-control task performance - and therefore it was considered that the thesis would flow better with the employment of this format.

Construction of thesis

Following this introductory chapter, the thesis contains a literature review, and subsequent chapters include seven individual studies, written as publishable papers (two of which have been published in peer-reviewed journals) and finally a discussion chapter, collating the findings from the seven studies and highlighting limitations and ideas for future research as well as outlining the implications the research brings and the general conclusions.

My contribution

I conducted all the research investigations myself, with guidance from my supervisors Dr. Sandra Sünram-Lea, Dr. Trevor Crawford and Dr. Emma Gowen. The design of each research study as well as the execution of each experiment was completed by me with guidance from my supervisors. There was an exception for paper five in which a third year undergraduate student, Kelly Richardson, provided assistance in data collection (see chapter seven). However all the data for this study was gathered in my presence. The student was involved for training purposes as this gave Kelly the opportunity to learn about the eye tracking technology as she was keen to learn more about designing and conducting eye tracking based experiments and their utility in such experimental designs.

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Self-control exertion; the ability to apply self-control across tasks over time: Literature Review

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Self-control exertion; the ability to apply self-control across tasks over time: Literature Review

Self-control

Chapter 16:32, in the book of proverbs in the Old Testament.

"Better a patient person than a warrior, one with self-control than one who takes a city."

What is self-control?

Self-control (or willpower) is involved in the regulation of behaviour and thoughts, and refers to the ability of overriding one response for another (Muraven & Baumeister, 2000). It is required for behaviours and situations where one controls automatic or impulsive responses for example, suppressing certain emotions in public or refraining from consuming unhealthy food while dieting (Inzlicht, Berkman & Elkins-Brown, 2016). A lack of self-control or one's failure to apply self-control is associated with high levels of impulsivity (Wills, Isai, Mendoza & Ainette., 2007; Boy, Evans, Edden, Lawrence, Singh, Husain, & Sumner 2011).

Self-control is linked to inhibitory control, one of the executive functions of the self's executive control system in addition to working memory, flexibility and planning (Miyake, Friedman, Emerson, Witzki, Howerter, & Waher , 2000; Diamond, 2013). Executive functions (EFs) are higher order cognitive processes of the frontal brain regions, involved in the top down processing of information (Beaver, Wright & Delisi, 2007). EFs are cognitively demanding and require the conscious and effortful control of behaviours, thoughts and feelings (Inzlicht, Legault & Teper, 2014a; Kool, McGuire, Rosen & Botvinick, 2010; Holding, 1983; van der Linden, Frese, & Meijman, 2003), which contrast with low order cognitive processes, which are more reflexive and automatic in nature (Miller & Wallis, 2009).

There is consensus that self-control exertion relies on activation of the frontal brain regions, namely the prefrontal cortex (PFC: Barkley, 2001; Beaver et al., 2007), specifically the dorso-lateral prefrontal cortex (DLPFC). Functional magnetic resonance imaging (fMRI) studies reliably reported greater activation in this area during self-control performance (Barkley 2001; Telzer, Masten, Berkman, Lieberman & Fuligni, 2011; Hare, Camerer & Rangel, 2009).

Moreover, evidence from the neuroscience literature highlights that the neural correlates of self-control includes a number of brain systems and networks, which are responsible for cognitive control processing particularly those that require top down control. These include the DLPFC, ventral lateral prefrontal cortex (VLPFC) and dorsal anterior cingulate cortex (ACC) (Inzlicht, et al., 2016).

Further, activation of the DLPFC, VLPFC, dorsal ACC and lateral parietal cortex have been widely reported (Cohen, Berkman & Lieberman, 2013; Inzlicht, et al., 2016; Stevens, Hurley & Taber, 2011). There is agreement that these brain areas are highly activated during self-control exertion (Inzlicht et al. ,2016). Neuroimaging evidence showed that in a group characterised with poor self-control – those involved in criminal behaviour - activation of the frontal lobes was weakened (Raine, Buchsbaum & LaCasse, 1997). Further, acting impulsively - a characteristic of poor self-control - is more commonly observed in patients that have brain damage to the frontal lobes (Brower & Price, 2001). Such patients emit habitual type behaviours and unlike healthy participants, demonstrate difficulty in planning and following instructions (Miller & Wallis, 2009).

Frequent use

Self-control is exercised daily (approximately three to four hours) and is widely applied to a variety of situations (Hoffman, Baumeister, Foerster & Vohs, 2012; Inzlicht, et al., 2016). Being able to frequently exert self-control is positively associated with maintaining good relationships, improved academic performance and positive prospects in the future (Moffitt, et al., 2011; Tangney, Baumeister & Boone, 2004).

Self-control is important for social order; ensuring societal norms and expectations are adhered to (Hoffman, et al., 2012; Baumeister, 2012). For example, some societal issues are argued to stem from weakened self-control such as violence, criminal activity (Raine, et al., 1997), and financial problems (Hagger, Wood, Stiff, & Chatzisarantis, 2010). Extending this, poor self-control is associated with other issues, including obesity (Skoranski, Most, Lutz-Stehl, Hoffman, Hassink & Simons, 2013), and compliance towards behaviours like exercising, quitting smoking (Hagger et al., 2013).

The resource depletion theory/strength model of self-control

Although regularly exercised and important for everyday functioning, and there being clear positive outcomes to possessing high levels of self-control, self-control impairment is common. Research evidence has consistently shown that continued self-control application is effortful with a gradual weakening in self-control performance occurring over time (Muraven & Baumeister, 2000; Baumeister, 2012). Specifically research demonstrated that individuals have difficulty completing two self-control tasks in close succession; typically the first is performed well but performance temporarily deteriorates in the second (Hagger et al., 2010; Crowell, Kelley & Schmeichel., 2014). Establishing why self-control ability weakens with repeated exertion, Baumeister, Heatherton and Tice (1994) developed the resource depletion theory/strength model of self-control (Baumeister, Vohs & Tice., 2007). Drawing on an energy perspective this theory posited that self-control relies on the availability of a limited energy resource with a temporary reduction leading to deterioration in subsequent performance in a second task; i.e. there is limited energy available to continue to fuel successful self-control exertion. This reduction in self-control resources following exertion was termed ‘ego depletion’ (Baumeister, et al., 2007). In response to this, a wealth of research was conducted (Converse & Deshon, 2009; Hagger et al., 2010), with studies typically administering a sequential two-task paradigm; an initial self-control task is completed - designed to reduce self-control resources - followed by a second self-control task, administered immediately after the first (Tyler & Burns, 2008; Hagger et al., 2010). With research implementing this paradigm, support for the resource model of self-control has been demonstrated widely; initially exerting self-control temporarily diminishes a general resource, resulting in performance decrements in subsequent self-control tasks (Muraven, Tice & Baumeister, 1998; Hagger et al., 2010). More than eighty studies robustly and consistently supported this (see meta-analysis by Hagger et al, 2010). Furthermore, the term ‘ego depletion’, has been cited over one thousand times demonstrating its’ wide research exploration and impact (Inzlicht & Schmeichel, 2012).

Evidence in support of the resource depletion theory/strength model of self-control (Baumeister et al., 2007)

Baumeister and colleagues (Baumesiter, Bratslavsky, Muraven & Tice, 1998) research showed that when participants were instructed to refrain from eating biscuits compared to radishes, they subsequently engaged in an unsolvable tracing task that required self-control for less time. Only participants provided with the biscuits had to exert self-control, which as the resource depletion theory outlines, resulted in less self-control resources being available for their implementation in the tracing task. Further evidence showed that, regulating mood during a video clip resulted in less time spent controlling one’s movements in an administered handgrip task (Muraven, et al., 1998). Monitoring prejudice responses during an interaction with a participant of a different rather than similar ethnic background resulted in weakened performance in a subsequent incongruent Stroop task (Stroop, 1935), which relies on self-control as one must override the automatic response of reading the word and instead state the colour of the word (Richeson & Shelton, 2003).

The effect of completing an initial self-control task on subsequent performance has been applied to spending levels (Ackerman, Goldstein, Shapiro & Bargh, 2009). For example, having to initially suppress hunger (utilising self-control) adversely affected one's ability to appropriately control spending levels; participants offered to purchase items for more money (Ackerman et al., 2009). Reiterating this, individuals were more prone to greater spending following an earlier activity where they were instructed to express emotion while reading an arduous piece of writing (Vohs & Faber, 2007).

Moreover, supporting the resource depletion theory, after completing a writing task and refraining from using the letter 'e' and spaces, participants were more likely to claim to have finished more of a subsequent maths task (Debono, Shmueli & Muraven, 2011). This was extended to the level of politeness participants projected towards the researcher at the end of testing; a reduction in politeness was observed for those that had previously applied self-control.

Further, applying the exploration of sequential self-control performance to unethical behaviours, research demonstrated that participants were more likely to cheat after prior self-control exertion (Gino, Schweitzer, Mead & Ariely, 2011). For example, compared to activities carried out in the morning, individuals were more likely to behave less ethically i.e. lie, cheat or act dishonestly later on in the day (Kouchaki & Smith, 2013). This was explained as being due to the fact that during the day, individuals actively engage in tasks that require self-control, resulting in the regular use of self-control resources, with limited resources thus available for later application (Kouchaki & Smith, 2013; Hoffman et al, 2012).

Applying the resource depletion theory to workplace productivity, Bucciol, Houser and Piovesan (2013) explored whether watching a video adversely affected workplace productivity - based on their performance in a subsequent maths task - to a greater extent than suppressing the temptation to watch the video while at work (using self-control). Those that resisted watching the video performed worse on the subsequent maths task. Consequently, if one uses self-control to suppress the urge to complete non-work related activities such as checking Facebook this could have an adverse impact on performance on subsequent work-related tasks such as in decision making, which relies on self-control (Hare et al., 2009). As decision making requires self-control and is effortful, if one is already in a state of ‘ego depletion’ when making a decision these may not be optimally achieved (Baumeister & al-Ghamdi, 2014; Joosten, Van Dijke, Van Hiel & De Cremer, 2014).

Suppressing emotions at work, within a customer services role, had a similar effect resulting in a reduction in performance in subsequent work-based tasks (Grandey, Rupp & Brice., 2015) Further, applying this to hoarding behaviour following the completion of a three minute incongruent Stroop task, participants were prone to a greater level of hoarding behaviour, than those that completed a congruent (control) Stroop task (Timpano & Schmidt, 2013).

Applying self-control findings even more widely, smokers instructed to resist eating brownies, subsequently smoked a greater number of cigarettes (Shmueli & Prochaska, 2009). Further, a greater level of alcohol was consumed after the completion of cognitively demanding and effortful tasks (Muraven, Collins, Shiffman, & Paty, 2005). Moreover, more donations were given to charity after self-control had been expended (Fennis, Janssen & Vohs, 2009).

Extending the findings to sport and exercise, a research study explored whether completing an initial task (erasing letters task) that required self-control had an adverse effect on basketball throwing ability while having to ignore distracting auditory messages. Participants who engaged in the initial self-control task performed less well in the throwing task; they were less able to ignore the distracting auditory information and successfully perform the throw ball task (Englert, Bertrams, Furley & Oudejans, 2015). However, a more recent study failed to extend this to the physical activity of running as engaging in self-control did not adversely affect subsequent running ability (Schücker & McMahon, 2016).

Neural activity and self-control performance over time

Activation of certain brain areas during self-control tasks which are considered to be responsible for such cognitive control processing - the DLPFC, VLPFC and dorsal ACC (Inzlicht, et al., 2016) – have been observed to be affected by prior self-control exertion, reflecting the pattern of a temporary deterioration in self-control performance. For example during the completion of two sequential self-control tasks – a thought suppression task followed by incongruent Stroop task – a reduction in Stroop performance was observed to correspond with a lowering in DLPFC activation (Friese, Binder, Luechinger, Boesiger & Rasch, 2013). Thus reduction in DLPFC activation was associated with being less able to successfully apply self-control in a second task following prior exertion. This finding was replicated; reduced DLPFC activation emerged during a subsequent task of self-control after initial exertion (Hedgcock, Vohs & Rao, 2012). A reduction in DLPFC activity thus appears to be reflective of a temporary reduction in self-control resources and the ability to continually apply self-control successfully.

Brain imaging studies also observed a role for the ACC in self-control, with this area activating at a comparable rate during both initial and subsequent tasks in a sequential two task paradigm despite performance deterioration in the second task (Hedgcock, et al., 2012). This area is argued to be involved in assessing when self-control is required, suggesting that the ability to recognise when a task requires self-control is not altered following prior self-control exertion, it is one's ability to further apply self-control that weakens (Hedgcock, et al., 2012).

Is glucose the resource, that fuels self-control processing?

Responding to the accumulation of evidence, research explored the factors that might modulate self-control performance (Hagger et al., 2010). More specifically, there was an attempt to address whether an actual energy resource directly fuels self-control. This pointed to evidence suggesting the substrate was glucose and when blood glucose availability falls, self-control performance weakens (Baumeister, 2012; Baumeister & Vohs, 2016). Thus rather than surmising – as a considerable pool of previous research on self-control had done – about the existence of a resource by solely examining performance in the second of two sequential tasks, researchers explored whether an actual energy resource fuels self-control (Inzlicht, Schmeichel & Macrae, 2014b).

Glucose is the primary energy source for the brain and is vital for its healthy functioning (Amiel, 1994). Glucose is consumed during cerebral activity, with levels reducing (Scholey, Harper & Kennedy, 2001). The brain has limited glucose storage capacity and relies on a continuous and sufficient supply (Amiel, 1994; McCall, 2004). However depending on the level of effort expended in a task/activity, cognitive processes may vary in the amount of energy required (i.e. glucose). Effortful, controlled executive processes have a significantly higher energy cost than automatic reflexive processes (Sunram-lea & Owen, 2017). Peripheral blood glucose levels are reported to be lowered during the completion of a cognitively demanding task and replenishing glucose levels enhances performance in these tasks (Kennedy & Scholey, 2000; Scholey, et al., 2001). Cognitively demanding tasks and in particular those relying on executive functions are sensitive to alterations in blood glucose availability.

Arguably there is a level of symmetry regarding peripheral levels of glucose in the blood and those in the brain (Lund-Anderson, 1979). Variations in blood glucose levels influence neural activity and thus cognitive performance (Sunram-Lea & Owen, 2017). Centrally, it has been argued that performing demanding cognitive tasks leads to a decrease in glucose activation in surrounding tissues, suggesting that the neurons draw on these glucose supplies. For example extracellular fluid (ECF) in rats was found to decrease when performing a complex maze memory task (McNay, Fries & Gold, 2000). There has also been the suggestion however that performing demanding cognitive tasks lowers peripheral levels of blood glucose (Scholey, Harper & Kennedy, 2001). Applying this to self-control – a high level cognitive ability - one could argue that when blood glucose levels are low as measured after a self-control task (Gailliot et al., 2007), cognitive function in one's ability to apply self-control is impaired.

Supporting the role of glucose in self-control performance, evidence revealed a reduction in blood glucose levels in participants that had engaged in an incongruent (rather than congruent) Stroop task (Fairclough & Houston, 2004). This observation was replicated in a series of studies in which blood glucose levels were measured before and after an attention control task (a video clip was played and the goal was to control one's attention and refrain from reading words presented on the screen), a Stroop task and an emotional regulation task (Gailliot et al., 2007). A reduction in peripheral blood glucose availability was observed after completion of each of the self-control tasks.

Secondary evidence for an association between a lowering in blood glucose levels and impaired self-control ability provided further support for the argument that self-control is influenced by alterations in blood glucose availability. For example, consuming alcohol impairs self-control and results in more impulsive behaviours (Baumeister et al., 1994). Specifically alcohol consumption also affects blood glucose metabolism; consuming alcohol initially leads to an increase in blood glucose but the insulin response some time later leads to a reduction in blood glucose (Volkow et al., 1990). This supports the suggestion that a reduction in glucose availability might be a contributing factor to self-control impairment (Gailliot & Baumeister, 2007). Importantly, alcohol reduces the supply of glucose to the prefrontal cortex, a prominent brain region underlying self-control (Giancola, 1999).

Further, correlational evidence demonstrated a relationship between low blood glucose and decrements in self-regulatory behaviours. Poor self-control is a risk factor for aggressive behaviour (DeWall, Deckman, Gailliot & Bushman, 2011) and it has been observed that individuals with poor glucose tolerance, diabetes mellitus and those with hypoglycaemia - which all present difficulties in effectively processing glucose - are prone to higher levels of aggression (Gailliot & Baumeister, 2007). Moreover, lower blood glucose levels in the evening correlated with higher levels of aggressive behaviour i.e. how well one was able to suppress emotions such as anger and aggression (Bushman, DeWall, Pond & Hanus, 2014). Although associative this supports the hypothesis that glucose availability influences successful self-control exertion.

Moreover, through various investigations, Gailliot et al (2007) provided more direct evidence for the role of glucose in self-control. Following a decline in peripheral blood glucose levels after applying self-control in an initial task, diminished performance on a subsequent self-control task (persevering on a complex tracing task) was observed. However, glucose administration before the second self-control act counteracted the detrimental effect of initial task completion (Gailliott et al, 2007). Reinforcing this, glucose ingestion has been directly observed to improve self-control performance despite the previous exertion of self-control (Masicampo & Baumeister, 2008). Additionally, DeWall, Baumeister, Gailliot and

Maner (2008) found participants were more reluctant to help another person if they had previously engaged in a self-control task (removing particular letters in a passage of text), yet the administration of a glucose drink (of approximately 140 calories) before the first task ameliorated this effect. As consuming a glucose solution produced greater levels of helping behaviour, this suggests that glucose plays a prominent role in self-control, temporarily decreasing after an initial act and thus weakening successful performance in a sequential self-control task unless one's glucose levels were replenished.

In response to Gailliot et al.'s (2007) findings, further studies supported the hypothesis that self-control appears to depend on glucose availability. Wang and Dvorak (2010) observed that despite initial self-control exertion, glucose relative to placebo administration led to participants forming better future decisions. However, a limitation of this investigation was that rather than a pure glucose (vs. placebo) solution being administered, either 'Sprite' and 'Sprite Zero' were consumed and used to manipulate blood glucose levels. It is difficult to separate the direct effect of glucose relative to the other ingredients on self-control ability, which somewhat weakens confidence in these findings.

Further, Xu, Bègue, Sauve and Bushman (2014a) observed that glucose administration (140 calories) led to an improvement in sequential self-control performance specifically following the completion of a self-control task. Participants' feelings of guilt during a subsequent task were reduced and they offered to provide fewer lottery tickets for another participant. However, this was counteracted by the administration of a glucose drink; feelings of guilt were higher and thus more lottery tickets were offered to the other participant.

Thus a large body of evidence has demonstrated that successful self-control exertion might depend on a limited pool of resources with that energy resource being glucose.

Is glucose really the resource?

However, research has challenged the relationship between glucose availability and self-control; scepticism exists about whether glucose directly fuels self-control (Inzlicht, et al., 2016). Although it is appealing to suggest that glucose fuels self-control ability i.e. the idea that a resource is running out (Evans, Boggero & Segerstrom, 2015), the evidence suggesting glucose is the energy resource responsible for self-control is inconsistent (Lange & Kurzban, 2014) with a recent meta-analysis highlighting this (see Dang, 2016)

Specifically, the idea that changes in glucose availability in the brain during cognitively effortful tasks, such as those requiring self-control are significant has been questioned. It has been argued that changes in central availability might be too small to result in deterioration in self-control performance (Kurzban, 2010; Beedie & Lane, 2012). For example, Positron emission tomography (PET) scanning showed that as little as a 1% increase in glucose use in areas of the brain during cognitively demanding tasks (Raichle & Mintun, 2006). Consequently, it is difficult to equate the findings of a lowering in blood glucose levels peripherally to those centrally in the brain (Kurzban, 2010).

Further, recent research failed to replicate Gailliot et al.'s (2007) findings that glucose levels significantly depleted following self-control exertion (Inzlicht, et al., 2016); later studies observed no significant changes in blood glucose levels following self-control application (Molden, Hui, Scholer, Meier, Noreen, D'Agostino, & Martin, 2012). Further, re-examining Gailliot et al.'s (2007) data, the observation that engaging in self-control significantly lowered blood glucose levels was disputed (Kurzban, 2010). Moreover, simply swilling and not ingesting glucose in the mouth was observed to enhance self-control after previous exertion (Sanders, Shirk, Burgin & Martin, 2012; Boyle, Lawton, Allen, Croden, Smith, & Dye, 2016), suggesting that metabolism of glucose was not necessary to counteract a temporary deterioration in self-control (Molden, et al., 2012; Hagger & Chatzisarantis, 2012). Consequently, it was argued that alternatively glucose might exert its beneficial effects on self-control performance indirectly. For example, glucose might be motivational and its presence in the mouth might stimulate brain areas, which are associated with reward (Chambers, Bridge & Jones, 2009).

The idea came about that triggering taste receptors in the mouth with a solution such as glucose might activate certain neural pathways and thus lead to an enhancement in performance. Therefore activation of these brain areas might help explain why performance in tasks can be improved (Chambers et al., 2009). Research evidence from neuroimaging showed that the sensing of glucose in the mouth triggered dopaminergic pathways in the striatum – the area that is activated for rewards- whereas a solution of equivalent sweetness did not (Kringelbach, 2004; Chambers et al., 2009). Specifically, Chambers et al (2009) observed that glucose as opposed to saccharin consumption stimulated parts of striatum, suggesting that it was not the sweetness of the drink but perhaps the caloric content of glucose that triggered this activation. Therefore evidence suggests that sensing glucose in the mouth may indicate some form of reward which then leads to the motivated injection of energy into any subsequent cognitive exertion (Molden et al., 2012).

However more recently using the sequential two task paradigm a study observed that neither the sensing of glucose in the mouth nor its' ingestion enhanced self-control performance following prior exertion (Lange & Eggert, 2014). This evidence suggested that self-control operates independently from glucose availability.

However, in response to this criticism, Baumeister and Vohs (2016) have argued that an association between blood glucose levels has been consistently observed within the literature; when blood glucose levels are low, self-control is poor. This is particularly strong if one looks at the link between the symptoms of diabetes and poor glucose regulation and poor self-control (DeWall, Pond & Bushman, 2010). Additionally, drinks and food products that do not contain glucose have not been observed to improve self-control performance (Gailliot et al., 2007). Thus according to Baumeister and Vohs (2016) there must be something about the physiological resource glucose. For example, other biochemical processes – along with glucose – might be linked to successful self-control performance such as adenosine (Baumeister & Vohs, 2016), which is a consequence of glucose metabolism. Specifically the binding of adenosine to adenosine receptors in the brain rises throughout the day. More adenosine binding leads to greater levels of tiredness. Tiredness induced from the adenosine binding might therefore play a role in the reduction in self-control performance. However it is difficult to observe why this would be specific to solely self-control ability. The role of glucose in self-control clearly needed more exploration, which this thesis aimed to explore.

Moreover, the role of a resource such as glucose in self-control performance has been questioned by recent evidence which appears difficult to interpret from solely a resource perspective (Inzlicht & Schmeichel, 2012; Inzlicht et al., 2016). For example motivation level, the offering of rewards such as of monetary value (Muraven & Slessareva, 2003), smoking cigarettes (Heckman, Ditre & Brandon, 2012), watching television (Derrick, 2013) as well as possessing certain beliefs and ideas about the nature of one's ability to exert self-control (Job, Dweck & Walton, 2010) all appear to restore the temporary deficiency in self-control performance one observes in the second of two sequential self-control tasks (Inzlicht et al., 2016). Further, factors such as sleep, (Barber & Munz, 2011; Barutchu, Carter, Hester & Levy, 2013), being made more self-aware (Alberts, Martijn & De Vries., 2011), praying relative to free thought (Friese & Wanke, 2014), informing participants that a task is easy as opposed to difficult (Giacomantonio, Ten Velden, & De Dreu, 2016), a resting period such as a break of ten minutes (Tyler & Burns, 2008), meditation and mindfulness (Friese, Messner & Schaffner 2012), engaging with the natural environment through being shown photographs of natural scenes (Chow & Lau., 2014), in addition to challenging individuals' perceptions that self-control tasks are exhausting, appear to remove the effects of 'ego depletion' when participants perform a second self-control act (Martijn, Tenbult, Merckelbach, Dreezens, de Vries, 2002). In addition, using a clock to naturally keep check on performance level counteracts the effects of self-control depletion (Wan & Sternthal, 2008). If self-control relied solely on one resource then it is difficult to see how these non-resource explanations could ameliorate the temporary deficiency often observed in a second task of self-control (Inzlicht et al., 2016).

Limitations/challenges to the resource depletion theory/strength model of self-control

Publication bias

A problem that exists across all scientific disciplines, but is particularly applicable to the self-control literature (Carter & McCullough, 2014) is the issue that studies, which produce non-significant findings, are less likely to be published (Wagenmakers, Wetzels, Borsboom & Van Der Maas, 2011); publications are often tied to significant results (Sutton, Song, Gilbody, & Abrams, 2000). Consequently, the research on self-control and the findings supporting the resource depletion theory – of a temporary deterioration in self-control ability occurring over time - could thus have been misrepresented with the level of support inflated. This has created scepticism about whether ego depletion is an actual phenomenon and leads to questions surrounding its' robustness and reliability (Hagger, & Chatzisarantis, 2014; Lurquin, Michaelson, Barker, Gustavson, von Bastian, Carruth, & Miyake., 2016; Lee, Chatzisarantis & Hagger, 2016). Responding to this, null findings have recently emerged in the published literature, which are discussed in the subsection below.

Responding to this and incorporating unpublished findings into a meta-analysis, Carter, Kofler, Forster, & McCullough (2015) questioned the ego depletion effect and challenged Hagger et al.'s (2010) previous meta-analysis. However, Cunningham and Baumeister (2016) have recently queried this noting that many of the studies that Carter et al. (2015) used were unpublished, with published ones being excluded from the analysis. Thus it is clear there is considerable debate surrounding self-control performance, which required further exploration.

Failure to replicate the effect

Murtagh and Todd's (2004) research failed to support the prior literature on self-control. Across two studies in which two sequential self-control tasks were administered (Stroop followed by handgrip task; thought suppression task followed by persistence in an anagram task), no temporary deficiency in self-control performance was observed in the second task, failing to support the response trajectory outlined by the resource depletion theory.

Further, a series of findings were published by Xu, Demos, Leahey, Hart, Trautvetter, Coward, Middleton, and Wing (2014b) which failed to replicate the typical response trajectory of the resource depletion theory; a drop in performance in the second of two sequential self-control tasks was not observed (Xu et al., 2014b). The failure to replicate wasn't due to methodological issues as all four studies employed tasks that had frequently been implemented in the self-control literature (Hagger et al., 2010). Moreover, Lurquin et al. (2016) responded to criticisms of prior research that the resource depletion theory has been exaggerated by research studies relying on the recruitment of small samples (Carter & MCCullough, 2014) and recruited a larger sample size (200 participants), administering two sequential cognitively demanding tasks to participants; video attention task (focusing attention on one aspect of the video and ignoring another part) followed by an operation span task (word recall task in which the presentation of the words that need to be recalled are alternated with mathematical problems). The authors' failed to replicate previous findings; working memory capacity did not differ based on level of prior self-control exertion in the initial attention control video task. Moreover, neither task difficulty nor task duration moderated these findings. However, the use of a working memory task could have led to the failure to observe a decline in performance as this task does not specifically tap self-control processes (Lurquin et al., 2016).

Methodological Limitations

Further, reviewing the literature on the relationship between glucose levels and self-control performance, it is evident that few studies which manipulated glucose levels via drink administration (such as Gailliot et al, 2007; DeWall et al, 2008; Masicampo & Baumeister, 2008), actually measured blood glucose levels. This requires attention as results were based on the inference that the glucose drink had an enhancing effect; replenishing depleted resources, thus preventing the likelihood of self-control impairment. The thesis addressed this by measuring peripheral blood glucose levels in all studies where glucose (vs placebo) solutions were administered.

However, there is doubt whether peripheral glucose levels assessed through finger prick measures lack sensitivity and research that used a Yellow springs instrument glucose analyser), which is considered a gold standard (see Modlen et al., 2012) - to measure changes in blood glucose levels - failed to replicate Gailliot et al's (2007) peripheral blood glucose findings.

Despite this, a number of studies have compared the YSI method, to popular finger prick devices, that use a lancet to collect blood samples, and reported comparable results (Cohen, Boyle, Delaney & Shaw, 2006; Khan, Vasquez, Gray, Wians & Kroll, 2006; Argollo, Faustino, Faustino, & Pedreira, 2010).

A further methodological limitation stems from participants not being given a pure glucose drink to consume in some of the studies on self-control. For example Wang and Dvorak (2010) administered and compared the effects of Sprite to Sprite zero on self-control. It is however difficult to isolate the effects of glucose from the other ingredients. Thus it is beneficial that studies interested in exploring the effects of glucose on self-control to administer pure glucose drinks.

Further, it is evident from the reading of the literature that various fasting durations were implemented in those studies that explored the relationship between self-control performance and blood glucose levels. It is difficult to thus form comparisons across studies. Indeed, if there are differences in the effects of blood glucose availability on self-control performance depending on the fasting duration then this could arguably provide more information about the relationship between glucose availability and self-control.

Alternative theories to the resource depletion theory (Baumesiter et al., 2007)

Resource allocation account of self-control (Beedie & Lane, 2012)

The resource allocation account (Beedie & Lane, 2012) maintains that a resource is involved in self-control but draws on a motivational perspective to understand why self-control ability temporarily reduces over time with repeated exertion (Masicampo, Martin & Anderson, 2014). It posits that a temporary deficiency in self-control does not stem from glucose depletion *per se* but from glucose not being allocated to a task because it is not viewed as a personal priority (Beedie & Lane, 2012); glucose is allocated to areas of the brain pertaining to tasks that are considered important and/or interesting. Based on Beedie and Lane’s (2012) resource allocation account that energy is allocated to tasks when motivation is high, Kazén, Kuhl and Leicht, (2014) argued that this would result in reported levels of sustained or enhanced blood glucose (Beedie & Lane, 2012; Kazén, Kuhl & Leicht, 2014). Thus the response trajectory typically observed in the literature of a temporary deficiency in self-control performance following prior exertion is reflective of low motivation. Supporting this, Kazén et al. (2014) observed that high motivation was paired with an increase in levels of peripheral blood glucose (measured using an 'Accu-Chek Aviva' device) during the completion of two sequential self-control tasks, supporting their argument that possessing the motivation to complete tasks resulted in heightened glucose. They reasoned that this meant that more energy had been injected into the tasks resulting in improved performance (Kazén et al., 2014).

Revision to the resource depletion theory

Acknowledging Beedie and Lane's (2012) resource allocation account, Baumeister and colleagues (Baumeister & Vohs, 2016) amended their original resource model to account for recent findings, namely that if one is high in motivation, one appears to perform a self-control task well despite prior exertion. The revised account argues that resources are allocated to a task based on level of motivation to complete the task but that selectivity in resource allocation only emerges, when resources are limited (Baumeister, 2014). Thus rather than self-control engagement draining resources completely, the revised model posits that through self-control engagement, resources are somewhat but not fully depleted and if one is motivated (by an important task or situation) one will allocate any remaining resources to successfully complete a self-control task.

Non-resource accounts of self-control

In contrast to the resource models, the shifting priorities account (Inzlicht et al., 2014b), labour/leisure trade off account (Kool & Botvinick, 2014), and opportunity cost model (Kurzban, Duckworth, Kable & Myers, 2013) all explain why a temporary impairment in self-control arises through repeated exertion from a motivational perspective (Inzlicht & Marcora, 2016). In contrast to the resource depletion theory (Baumeister et al., 2007) they posit that the temporary deficiency in self-control ability does not arise from resource limitation, but from a lowering in motivation level. These theories are discussed below.

Shifting priorities / process model (Inzlicht & Schmeichel, 2012; Inzlicht et al., 2014a, 2014b)

The 'process model/shifting priorities model' argues that a temporary deficiency in self-control ability is associated with a lowering in one's motivation to exert self-control (Lee et al., 2016); as self-control is applied, motivation wanes over time (Inzlicht et al., 2014b). Thus a reduction in self-control reflects an alteration or shift in one's priorities i.e. reluctance to continue to apply self-control in a situation (Masicampo, et al., 2014); effortful tasks are favoured less over time and individuals only perform effortful tasks that they find interesting and enjoyable (Inzlicht & Schmeichel, 2012; Inzlicht, et al., 2016). An incentive or heightened levels of intrinsic motivation however counteracts this and self-control is successfully applied despite prior exertion.

Supporting this, a temporary deterioration in self-control can be ameliorated by activities that are motivating or rewarding and encourage the application of effort, such as smoking a cigarette (Heckman, et al., 2012), meditating (Yusainy & Lawrence, 2015), and praying (Friese & Wanke, 2014). Further, changing the value of the task may also be a way of motivating one to perform a second task well despite prior exertion (Inzlicht et al., 2014b). For example, altering the way in which task instructions are worded such as illustrating that one has a choice to complete the task (Kazén et al., 2014) or framing a task as a 'fun activity' rather than a 'work related task' (Werle, Wansink & Payne., 2014) have both been observed to enhance performance.

Although supportive of this theory, Dang, Xiao and Dewitte (2014) suggests that the theory must also take into account the involvement of some sort of cognitive mechanism. Specifically if an initial task demands cognitive resources and processes that are different to a subsequent task, one will need to activate these different processes to then successfully engage in the subsequent task. This adjustment arguably takes time and consequently adds to the explanation as to why the first task negatively affects performance in the second. If however, there is sufficient time to adapt to the control processes of the first task, no adverse effect on performance in the second task should be found (Dang, Dewitte, Mao, Xiao & Shi., 2013). When this sort of adaptation is possible therefore, the effect of motivation on counteracting any depletion effects is weakened i.e. not needed.

Labour/leisure trade off account (Kool & Botvincik., 2014)

This theory argues that after engaging in a self-control task, individuals assess both the costs and benefits of continued cognitive exertion, thus evaluating whether it is beneficial to further exert cognitive effort in a subsequent complex task. Although they might be 'costly', if one is provided with rewards or incentives to complete a task then one is more likely to engage in subsequent demanding cognitive activities. Arguably this account is able to accommodate for the findings that one's level of motivation or their belief about self-control capacity can moderate depletion **(**Kool & Botvincik., 2014).

Opportunity cost model (Kurzban, et al., 2013)

Similar to the shifting priorities account (Inzlicht et al., 2014b) and the cost/benefit analysis account (Kool & Botvinick, 2014), the opportunity cost model argues that engaging in tasks that demand higher level cognition like self-control provides an indication that an increased amount of effort needs to be applied to the activity. One then calculates the value of applying further effort in an equally cognitively demanding task. For example, if one has already applied self-control in an incongruent version of the Stroop task and expended high cognitive effort, a temporary deterioration is more likely to occur when one is faced with the challenge of completing a second task or more trials of the Stroop task (Kurzban et al., 2013). The extent that a task carries costs depends on the cognitive processes recruited; the more processes involved the larger the cost and level of effort expended. According to this notion, completing an initial dual task, which draws on two executive functions, such as inhibitory control as well as working memory, would have a larger opportunity cost as more cognitive processes are being used and it is thus more likely to observe a drop in performance in the subsequent task.

However, drawing on motivation if a task is deemed important and interesting, successful engagement in both initial and subsequent tasks would occur. For example, providing a monetary incentive for task engagement, attaching personal meaning to task completion, have both been observed to ameliorate any temporary deterioration in self-control performance (Muraven & Slessareva, 2003). From an opportunity cost perspective, being motivated to complete a task ameliorates the view that a task has a high opportunity cost and thus prevents weakened performance. Therefore, this model predicts that as well as performance potentially weakening over time (if one is not motivated), subsequent task performance could also be enhanced.

The dual component theory of inhibition regulation (Reynolds & McCrea, 2016)

This model argues that a reduction in self-control performance in the second of two sequential tasks is not always due to self-control failure, but that it depends on the context (Reynolds & McCrea, 2016). Further, it removes the resource component by re-phrasing ego depletion to the ‘inhibition termination effect’ arguing that nothing depletes. Taking an information processing perspective, this model argues there is a monitoring component (which notices when an automatic type of behaviour requires suppression) and a threshold component (which refers to one's tolerance level for engaging in self-control) and if the threshold component is not reached self-control is continually applied. However, when the threshold is reached, a temporary deficiency in self-control occurs, which is likely to happen when a task is considered highly effortful. The initial task draws one nearer to the threshold limit, resulting in one being less likely to continually apply self-control. According to this theory, individuals consider how tempting a particular behaviour is, how much effort is needed and how willing one is to engage and complete a task. However the tolerance for engaging in self-control might be altered, for example, if the task is framed differently. Illustrating this, research has shown that children more successfully suppressed the temptation to eat a marshmallow if they pretended it was a cloud (Mischel, 2014). Further, if participants were primed that a task was fun rather than linked to work, they were more likely to successfully complete that task (Werle et al., 2014).

Motivation

It is clear from the self-control literature that the more recent research findings and the proposed alternate theories to the resource depletion theory take a motivational perspective on self-control, arguing therefore that level of motivation plays a key role in self-control. Motivation thus encourages one to act with a specific aim or goal and can be defined as something that "energises and guides behaviour toward reaching a particular goal" (Sansone & Harackiewicz, 2000). When one is motivated, energy is applied to tasks and activities (Ryan & Deci, 2000). One form of motivation that is particularly relevant to the studies reported in this thesis is the concept of intrinsic motivation. When one is intrinsically motivated, tasks are completed because they are perceived as interesting or important. This contrasts with extrinsic motivation where one engages in an activity for an external reason such as to receive a reward.

Interestingly, there is evidence to suggest that it can be detrimental for task performance to have both. For example, intrinsic motivation combined with a reward (extrinsic motivation) based on performance ability, had a negative effect on level of intrinsic motivation. For example, Cameron and Pierce (1994) demonstrated that when a young child was provided with an incentive to draw despite already finding drawing interesting, they were then more likely to stop drawing if the reward was withdrawn.

For the purposes of this thesis, we particularly focused on examining the relationship between sequential self-control performance and intrinsic motivation. This seemed appropriate, particularly if we consider the theories – the resource allocation account and shifting priorities account – which base task engagement on the level of interest in a task and ones' desire to apply effort. For example, drawing on self-determination theory having intrinsic motivation (a form of autonomous motivation) to complete a task means it is a task one wants to complete because it is interesting and enjoyable.

Self-awareness and the link to motivation

Research showed that priming self-awareness counteracted a temporary deficiency in self-control in the second of two sequential tasks (Alberts, et al., 2011). This is consistent with evidence, which showed children consumed less food when a mirror was placed in front of them, as this heightened their self-awareness towards what they were doing (Beaman, Klentz, Diener & Svanum, 1979). Arguably increasing self-awareness primes one to their level of performance, which motivates successful performance (Alberts et al., 2011). For example, raising self-awareness might result in comparing performance to a social standard, which in turn results in having the motivation to perform well. We specifically attempted to replicate Albert et al's (2011) findings; that self-awareness ameliorates any temporary deficiency in self-control in a second task of self-control despite prior application. We also explored the relationship between self-awareness and intrinsic motivation on self-control performance over time measuring levels of intrinsic motivation towards the second task to observe whether any moderating effect of self-awareness stemmed from an alteration in level of motivation.

Individual differences in self-control

Individual differences observably exist in one's natural ability to apply self-control successfully (Tangney, et al., 2004). There is evidence to suggest that those with high levels of trait self-control – typically measured using self-reports such as Tangney et al.'s (2004) scale - perform self-control tasks better than those low in trait self-control. For example the higher one's ratings of impulsivity, the greater the length of time taken to perform an executive control task (Keilp, Sackeim & Mann, 2005). Thus individual differences in self-rated levels of trait self-control appear to moderate the successful application of self-control.

Specific to investigations assessing self-control performance over time – where two sequential self-control tasks are administered - there is growing evidence that individual differences in self-control moderate the adverse effect that initial self-control exertion has on subsequent self-control performance (Dvorak & Simons, 2009). Those high in trait self-control were observed to perform better in a subsequent self-control task following prior exertion than those low in self-control (Muraven, et al., 2005; Gailliot et al., 2007). Further, in Mischel's famous Marshmallow Experiment (Mischel, 2014), children with better levels of self-control found resisting eating a marshmallow that was presented to them easier. These children also used creative strategies to stop them from eating the marshmallows such as imagining them as another object such as cotton wool or a cloud.

Findings however have been inconsistent in this area. For example, congruent with the resource depletion theory, initially exerting self-control had an adverse effect on subsequent self-control exertion but this was not moderated by individual differences in self-control (Freeman & Muraven, 2010). Thus challenging prior observations, high trait self-control did not moderate the effects of self-control depletion on subsequent exertion.

Further incongruent evidence showed that after the exertion of self-control in a Stroop task, individuals characterised high as opposed to low in self-control [as assessed using Tangney, et al. (2004) self-control scale] consumed more chocolate after the task. Against expectations, individuals high in trait self-control were less able to resist the tempting food (Imhoff, Schmidt, & Gerstenberg, 2013). Reiterating this, Imhoff et al. (2013) observed that after initial self-control engagement participants high in trait self-control made more hazardous choices in a subsequent decision making task.

Thus the findings on the moderating effects of trait self-control on sequential self-control task performance appear to be inconclusive. Although some research findings suggest that having high levels of trait self-control results in being less vulnerable to self-control depletion, others have failed to observe this (Salmon, Adriaanse, De Vet, Fennis & De Ridder, 2014). More research was therefore required to examine individual differences in self-control and the extent to which these differences may have moderating effects on self-control performance following prior exertion. The work outlined in this thesis thus aimed to address this further by incorporating a self-reported measure of trait self-control in the studies to explore whether individual differences in levels of trait self-control has any modulating effects on sequential self-control task performance.

There has been some consideration of the reasons for the mixed/inconclusive findings with respect to the moderation of the self-control depletion effect by trait self-control. For example Imhoff, Schmidt and Gerstenberg (2013) reasoned that it might stem from problems with relying on self-reported measures. It could be argued that they are simply inaccurate and lack validity so one should not rely on these for explaining the findings (Imhoff et al, 2013); other methods should be considered to assess differences in trait self-control. Alternatively it could be argued that there might be strong moderating factors which might not have been measured such as motivation. Examining the literature, the studies reporting motivation effects on self-control have not also measured trait self-control. This therefore requires investigation.

Limited beliefs about willpower

Research has suggested that one's belief in the amount of willpower one has modulates any ego depletion effect. Specifically those that believe there is no limit to self-control ability perform well in both self-control tasks in a sequential paradigm; those that do not show the typical ego depletion effect of a temporary deterioration in self-control performance over time (Job, Dweck & Walton, 2010). There has been consistent evidence in support of this observation in recent years (Inzlicht, Schmeichel & Macrae, 2014b). Consequently for the purposes of this thesis we also wanted to tap into this observation and explore whether beliefs about willpower capacity is a possible factor that influences one's ability to apply self-control over time.

To consider: Tasks employed to assess the effects of self-control depletion

A wide range of tasks have been employed across the literature to investigate self-control performance using a sequential task paradigm. According to Hagger et al.'s (2010) meta-analysis frequently administered initial self-control tasks designed to deplete self-control resources often include a thought suppression (typically of a white bear) task, an erasing letters task, controlling attention while watching a video, and the incongruent Stroop task. Further, tasks regularly used as the dependent measure of self-control (second task in a sequential two task paradigm) include the Stroop task, persistence based measures such as a controlled handgrip task, and complex but unsolvable puzzles and tracing tasks. Others include, the go-no-go, decision based activities and food selection and choice tasks (Hagger et al., 2010).

For the purpose of this thesis we employed frequently used cognitive tasks to measure self-control (Stroop, attention video and antisaccade tasks). One could argue that the cognitive measures employed were less ecologically valid than for example previous tasks that required one to resist caloric food intake. However the rationale behind the employment of these cognitive measures was that they would provide a somewhat purer evaluation of self-control as there were less likely to be inter-individual differences based on eating restraint level. Specifically there are individual differences in how easy it is to exert restraint when presented with food.

Stroop task

The incongruent Stroop task requires self-control as one must suppress/override the automatic response of reading the word and state instead the ink colour of the word (Govorun & Payne, 2006; Webb & Sheeran 2003; Fennis, et al., 2009; Inzlicht, et al., 2016). The Stroop task (Stroop, 1935) has been frequently employed in the self-control literature as both the initial depleting task (e.g. Bray, Ginis, Hicks & Woodgate, 2008; Martin, Ginis & Bray, 2010; Bruyneel, DeWitte, Franses & Dekimpe, 2009; Timpano & Schmidt, 2013) and the dependent measure of self-control (e.g. Richeson & Shelton, 2003; Gailliot et al., 2007). Versions implemented include paper based (e.g. Neshat-Doost, Dalgleish & Golden, 2008), and computerised versions (e.g. Goto & Kusumi, 2013). A specific computerised incongruent Stroop task originally designed by Wallace and Baumeister (2002) has been employed with some regularity in studies assessing self-control performance over time (Hagger, et al., 2010). In this modified Stroop task, participants are instructed to respond to the ink colour of 135 words but additionally for one of the ink colour words (usually red) this instruction has to be ignored and the actual word stated. Due to the required strategy switch, this task demands more cognitive resources (Wallace & Baumeister, 2002) and was thus designed to specifically aid in depleting self-control. Due to it being more cognitively demanding, the experimental studies within this thesis which used the Stroop task – mainly as the initial task – employed this version.

Attention control video task

The attention control video task has been regularly implemented in studies assessing sequential self-control task performance as the initial task (e.g. Yusainy & Lawrence, 2015; Chow & Lau., 2014; Gailiot et al., 2007; Wenzel, Connor & Kubiak, 2013; Masicampo & Baumesiter, 2008; Pocheptsova, Amir, Dhar, & Baumeister, 2009; Finkel, DeWall, Slotter, Oaten, & Foshee, 2009; Gino et al., 2011; Schmeichel, 2007; Hagger et al., 2010). This task involves watching a six-minute video (without sound) of a female speaking on the left hand side of the screen, while a word is presented sequentially every 10seconds on the right hand side. In the self-control condition, participants are instructed to ignore the words and focus on the female speaking.

The antisaccade task

A potential problem integral to the existing research on self-control, is the difficulty in finding congruency in the tasks used to measure self-control (Hagger, et al, 2010) and how self-control has been operationalised (Reynolds & McCrea., 2016). As alluded to above a number of different self-control tasks have been used to assess self-control ability across two sequential tasks (Duckworth & Kern, 2011). While growing evidence suggests self-control exertion weakens over time, the evidence has not yet been validated using a "biomarker" of self-control (Hagger et al., 2010).

Although using a variety of tasks illustrates the wide applicability of the ego depletion effect i.e. a temporary deficiency in self-control performance following prior exertion, findings across studies have been inconsistent. One of the thesis' aims was to address this by employing a novel task – the antisaccade eye movement task (Hallett, 1978) - as a more objective measure of self-control in an attempt to explore this as a potential biomarker of self-control. Assessing inhibitory ability and thus requiring conscious higher order cognitive processing and purposeful action, the antisaccade task requires generation of a voluntary saccadic eye-movement away from a target and suppression of the automatic response of looking at the target (McDowell, Dyckman, Austin & Clementz, 2008). The antisaccade task has been widely applied across healthy populations as well as various patient groups such as those with Schizophrenia, Alzheimer's Disease and Parkinson's Disease (Hutton & Ettinger, 2006; Ettinger, Antonova, Crawford, Mitterschiffthaler, Goswani, Sharma, & Kumari., 2015), making it a task that can be easily administered and understood. Additionally, a strength of this task is that it requires the single modality of vision for both processing the stimulus and the behavioural response. Previous tasks have tapped two modalities with for example the stimulus being encoded visually followed by an auditory or motor response. The switching of task modalities might have limited the 'purer' and more direct assessment of self-control ability (Luna, Garver, Urban, Lazar & Sweeney, 2004).

Moreover, the antisaccade task correlates well with alternative and frequently used measures of self-control such as the Stroop task (Brewer, Spillers, McMillan & Unsworth, 2011) and is linked to the brain areas associated with the self's executive control system such as the prefrontal cortex (PFC; Hutton & Ettinger, 2006; McDowell et al., 2008). fMRI analysis showed that correcting directional errors (erroneous eye movements towards the target) in the antisaccade task was associated with greater activation in the frontal and parietal regions of the brain prior to stimulus onset. Further, correct rather than erroneous responses are found to recruit additional brain regions; more activation was observed in the right DLPFC and ACC (Ford, Goltz, Brown, & Everling, 2005). As mentioned above, these areas are also activated during behavioural measures of self-control (Inzlicht, et al., 2016). Consequently, implementing the antisaccade task in further research, which examines self-control performance over time was appropriate, as it activates similar brain areas to other self-control tasks and is a more direct measure of self-control.

In terms of outcome measures derived from the task, antisaccade performance can be compared to prosaccade task performance. In the prosaccade task, a saccade is made towards the target, requiring no inhibitory control but an automatic response. The inhibitory processes required by the antisaccade task heightens saccade latency; prosaccade reaction times (RTs) typically have an average of 190 msecs whereas antisaccade responses are approximately 100 msecs slower (Hutton, 2008). The differences in brain activation in the two tasks reiterates this; although similar neural circuitry are recruited across both tasks, the prefrontal brain regions are activated more significantly in the antisaccade task, with stimulation of additional neural regions including the DLPFC (Domagalik, Beldzik, Fafrowicz, Oginska, & Marek, 2012) and ACC. Patients with damage to the frontal eye fields (FEFs) perform slower correct antisaccade responses and those with DLPFC damage conduct more antisaccade errors and find inhibition of a prosaccade difficult (Taylor, 2011; McDowell et al., 2008).

We aimed to administer both the prosaccade and antisaccade tasks within the experimental studies in this thesis. Administering both tasks would separate the effect that initially exerting self-control has on subsequent performance on saccadic eye movements in general compared to specific inhibitory control in the antisaccade task.

To the best of the author's knowledge only one study previously employed the antisaccade task in an investigation that examined sequential self-control task performance. Specifically, the antisaccade task was implemented as the initial depleting task and a Stroop task was subsequently administered and used to assess subsequent self-control peformance. The antisaccade task was therefore implemented to deplete self-control resources (Brewer, et al, 2011). No temporary impairment in self-control performance in the Stroop task following prior exertion in the antisaccade task was observed. However, the duration of the antisaccade task– it lasted 30 minutes (Brewer et al., 2011) –did not reflect previous studies which implemented shorter tasks (varying from approximately three to seven minutes). It could be argued that the reason why no reduction in subsequent Stroop performance was observed might stem from the length of time participants spent of the initial antisaccade task and this resulted in participants adapting to the task (Dang, et al., 2014). This would support the adaptation theory (see section on adaptation account below for more details).

This thesis aimed to more closely replicate existing methodologies and studies employed a shorter version of the antisaccade task to allow comparison to previous studies using tasks of similar duration. Further, as the antisaccade task had only previously been employed as the initial depleting task, we therefore employed different research designs using the antisaccade task as both the initial and dependent measure of self-control.

Antisaccade task and performance moderators

Previous research has examined the effects of various psychoactive substances, on antisaccade performance (Hutton & Ettinger, 2006). For example, nicotine had a positive effect on performance resulting in a decrease in both speed of response and the production of directional errors in the antisaccade task (Rycroft, Hutton & Rusted, 2006). We therefore addressed a gap in the literature by assessing whether saccade performance is sensitive to changes in glucose availability.

Further, previous research which explored the moderating effects of extrinsic motivation on antisaccade performance examined whether the offering of rewards influenced performance. For example, a number of studies observed a greater production of directional errors in the antisacacde task by healthy participants under non-reward compared to reward conditions (Duka, & Lupp, 1997; Padmanabhan, Geier, Ordaz, Teslovich, & Luna 2011; Mueller, Hardin, Korelitz, Daniele, Bemis, Dozier, Peloso, Maheu, Pine, & Ernst, 2012). This was also demonstrated for speed of antisaccade responses with participants in reward conditions performing better (at a faster rate). To the author's knowledge no study has examined the moderating effects of intrinsic motivation on antisaccade performance using a self-control depletion paradigm following prior self-control exertion; this thesis thus addressed a research gap.

Therefore, one of the main aims of this thesis was to explore the effect that glucose and intrinsic motivation level had on antisaccade performance following the prior application of self-control. More specifically, we aimed to assess whether high compared to low motivation and/or increased glucose availability results in faster or more accurate performance on the antisaccade task.

To consider: Task number

Typically, research which has examined the resource depletion theory/strength model of self-control (Baumeister et al., 2007) adopted a sequential two task paradigm in which participants engaged in an initial depleting (vs. control) task followed by a second dependent measure of self-control (Hagger et al., 2010). Although insightful, this has raised a question over whether ego depletion can be generalised to situations in which two or more initial tasks are completed.

The few studies that have addressed this provided mixed support for the strength model of self-control (Baumeister et al., 2007), which would predict that greater cognitive exertion through completing more initial tasks would produce more prominent depletion effects in a subsequent task. Consistent with this, evidence showed that completing two initial self-control tasks led to a weakened performance on a subsequent third task, compared to one initial task (Vohs, Baumeister & Schmeichel, 2012). Incongruent to this performance, in a third task was observed to improve following prior self-control exertion (Converse & DeShon, 2009). Completing one complex rather than a simpler task impaired performance on a subsequent task, supporting the resource depletion theory but completing two initially complex tasks enhanced performance in a later third task, challenging the resource depletion account (Converse & DeShon, 2009).

Further, motivation had a moderating effect on subsequent self-control performance but only for those that completed two sequential self-control tasks. In contrast, completing three self-control tasks in close succession resulted in a weaker performance in a third task by those high in motivation (Graham, Bray & Ginis, 2014). Thus when self-control resources were depleted rigorously (e.g. following the completion of two initial self-control exercises before a subsequent task) those higher in autonomous motivation performed a third task less well. Arguably having more autonomous motivation resulted in the exertion of greater effort in the two earlier tasks and subsequently a diminished level of resources were available for the last task. The authors argue that these findings provide support for the strength model of self-control as high motivation restored depletion only in the short term; performance weakened in later tasks suggesting that resource depletion arises after the exertion of effort over a longer period of time (Graham, et al., 2014).

However, administering four sequential tasks (Yusainy & Lawrence, 2015) supporting the strength model of self-control, performance in the second task was weaker by those that had previously exerted self-control compared to those that had not. Administering mindfulness training however moderated performance and participants performed less aggressively (higher levels of self-control) on a subsequent third task. However performance in the fourth task was not adversely influenced by engaging in any of the earlier tasks. The authors argued that this stemmed from participants being aware that this was the final task of the experiment and thus were motivated to finish the tasks. This somewhat challenges Graham et al.'s (2014) study as motivation instead enhanced and restored self-control ability in the longer term. The authors also suggested that any improved performance may have arisen from one adapting to the experimental situations. This is in line with the adaptation account, which the following section discusses in detail.

Research thus needed to widen the examination of the effects of depletion beyond studies with two task designs to those that contain three or more sequential tasks (Converse & DeShon, 2009).

Adaptation account: learned industriousness

Adaptation and theories of learned industriousness suggest that engaging in more than one initial task enhances performance allowing one to adapt to the demands and challenges of the tasks over time (Converse & Deshon, 2009). Having time to adapt to the demands of the situation by performing a task over a longer time period could also have an enhancing effect on subsequent performance and counteract any depletion effects (Dang, et al., 2013). Illustrating this, Brewer et al. (2011) observed that prior engagement in a 40 minute antisaccade task had no adverse effect on subsequent Stroop task performance. This is in line with Dang et al.'s (2014) suggestion that the duration of the task may have allowed time to adapt to the initial task resulting in no observed impairment in later Stroop performance.

Further evidence supporting this showed that completing three rather than one initial task before engaging in a writing exercise enhanced one's writing ability (Eisenberger, Masterson & McDermitt, 1982). Moreover, implementing a three task design (two handgrip endurance exercises followed by the Wisconsin Card Sorting Task; WCST), performance was observed to decline as expected by the resource depletion theory in the second handgrip task but not in the WCST (Graham & Bray, 2012). Further, Carter and McCullough (2013) observed that participants completing two initial self-control tasks performed well in a subsequent cognitively demanding working memory task (the Operation Span task), providing further support for the adaptation account.

Further, engaging in two self-control tasks has been shown to lead to weakened performance in the second task, whereas engaging in a series of more than two sequential tasks counteracts any temporary impairment in performance (Xiao, Dang, Mao & Liljedahl, 2014). Thus somewhat congruent with the adaptation account and Carter and McCullough's (2013) study, it appears that the more one exerts effort the better performance is observed to be in later tasks, thus challenging the premise of the resource depletion theory.

Similar versus dissimilar task administration

Another debate inherent within the literature on self-control concerns the type of tasks and/or combination of tasks that are employed to assess self-control performance across sequential tasks. In particular, there is disagreement whether performance differences depend on whether similar (or identical) or dissimilar tasks are sequentially completed. According to the resource depletion account, regardless of the similarity between the self-control tasks the energy resources available would diminish after exerting effort in the first task leading to a diminished level of performance in a second task. Supporting this, the sequential administration of two identical handgrip tasks led to a weaker performance in the second task (Graham & Bray, 2012). Thus regardless of the similarity between the two tasks, continued cognitive exertion decreased the ability to continually perform well.

However, there is evidence to suggest that engaging in two sequentially dissimilar tasks produced a weaker performance in the second task but completing two similar (or identical) tasks did not (DeWitte, Bruyneel & Geyskens, 2009). A temporary impairment in performance in a second task was restricted to completing two different tasks (Wenzel, et al., 2013). According to Lange (2015) if the typical depletion effect is not observed with the completion of two identical tasks, then the validity of the resource depletion account should be questioned. This is something that needed to be addressed and therefore in paper two (chapter four) of this thesis the sequential administration of identical tasks was compared to the completion of dissimilar tasks on one's ability to continually apply self-control.

Conflict monitoring theory; a cognitive control perspective: From a cognitive control perspective (Botvinick, Braver, Barch, Carter, & Cohen 2001) and specifically the conflict monitoring theory, a diminished performance in a second task reflects the challenge of attending to a different task and altering the format of one's response to support the new task. For example, completing two of the same tasks in a sequential order e.g. two incongruent Stroop tasks, does not present this challenge as the response in both tasks is the same (Dang, et al., 2014) and therefore according to the conflict monitoring theory a temporary reduction in performance in the second task would not be expected.

Consistent with this account, Dewitte, et al. (2009) showed that administering two similar tasks produced no subsequent deterioration in the second. However, applying self-control initially in a dissimilar thought suppression task led to a weakened in self-control performance in a subsequent shape and letter matching task. Further, following the completion of an initial Stroop task, only participants that engaged in a different second task (resisting sweets) as opposed to the same task (the Stroop) displayed a weakened ability to perform the second task (Wenzel et al., 2013). Thus a temporary deterioration in performance in the second task of two sequential self-control tasks was only observed if the tasks differed. Further research is required to examine self-control performance ability following the sequential administration of two dissimilar self-control tasks compared to two identical self-control tasks. This thesis attempted to address this research area in paper two (see chapter four).

General cognitive depletion vs. self-control (domain specific) depletion

The thesis also aimed to explore whether a temporary deficiency in performance following prior exertion was specific to self-control tasks or whether this response trajectory could be generalised to other higher levels forms of cognition, namely other EFs, such as planning and working memory ability (Diamond, 2013).

Domain specific account

It has been argued that depletion effects are domain specific and performance in a later task would only be affected by an initial task if both tasks tapped the same executive control processes; engaging in a task that relied on complex cognition weakens performance in a task that demands a similar level of cognition (van der Linden, et al., 2003). For example, completing a working memory task impaired performance in a semantic and episodic memory task. Yet engaging in a ‘stop signal’ task did not weaken performance in a task that required one to produce certain verbs in response to certain nouns (Persson, Welsh, Jonides & Reuter-Lorenz,2007).

Reinforcing this notion, brain imaging studies observed that different EFs stimulate dissimilar brain areas (Was, 2007). For example, working memory and inhibitory control trigger disparate sections of the prefrontal cortex (PFC). Thus if different EF tests appear to activate different parts of the brain it could be suggested that the impact that completing a task of one EF has on a subsequent task of a different EF should be minimal (Persson, Larsson & Reuter-Lorenz., 2013). For example, research by Vosgerau, Bruyneel, Dhar and Wertenbroch, (2008) showed that memory recall was less impaired following self-control exertion than following the completion of a working memory test. Participants either completed an initial 50 word Stroop task an or initial concurrent digit retention (working memory) task followed by a memory task, in which participants had to recall information from an earlier part of the experiment about a holiday resort. Both groups remembered less information about the holiday but those that completed the digit retention task first, performed worse. Vosgerau et al. (2008) reasoned that because the memory task did not draw on self-control resources, completing the initial Stroop task did not diminish one's ability to remember items. This supports the resource depletion/strength model of self-control and thus a domain specific account, which argues that exerting self-control only impairs one's subsequent ability to exert self-control, not tasks that do not tap self-control resources. Thus a reduction in self-control capacity does not reflect a reduction in cognitive capacity overall (Cowell, 2012).

However a degree of negative transfer (Brewer et al., 2011) was still observed between the two tasks (Vosgearu et al., 2008). Although the effect was small, exerting self-control led to a weaker performance in a later task, which did not pertain to self-control ability (Vosgearu et al., 2008). Vosgearu et al.'s (2008) findings could lead one to question the domain specific account of depletion, instead providing support for general cognitive depletion.

General cognitive resource depletion

Although the resource depletion theory has been supported by a wealth of research (Hagger, Wood, Stiff & Chatzisarantis, 2010), there is evidence to suggest that depletion effects might be more general and extend to other higher level forms of cognition - involved in the top-down processing of information - such as EFs like working memory and task switching (Conway & Engle, 1996; Ackerman & Kanfer, 2009; Cook, Ball & Brewer., 2014).

For example indirect support for this more general resource account comes from evidence showing that performance in tasks, which measure different EFs appear to correlate well with each other and also activate the same brain areas, namely the PFC. Further, those low in working memory capacity displayed a reduced performance on an emotion regulation task, which required self-control (Schmeichel, Volokhov, & Demareee, 2008). Thus different EFs appear to influence other EFs, suggesting they rely on similar resources or processes.

Moreover although within a typical resource depletion paradigm the vast majority of studies administered two sequential tasks that both tapped self-control, examining the literature it is evident that some studies paired a self-control task with other executive control tasks such as working memory or autobiographical memory tasks (e.g. Schmeichel, 2007; Neshat-Doost, et al., 2008; Clarkson, Hirt, Chapman, & Jia., 2011). Schmeichel (2007) for example observed that previously engaging in a self-control task led to an impaired performance on a subsequent working memory task, thus extending the depletion effect to another executive control task (Cook et al., 2014). Reinforcing this, Clarkson et al. (2011) conducted a study where they administered an erasing letters task followed by a subsequent working memory task in which participants were instructed to remember letters during a mathematical task. The results revealed that those informed after completing the first task they had reduced resources displayed a weakened working memory performance than those told they had ample resources. This suggests that performance in a cognitive demanding task can be negatively influenced by prior performance and/or information about one's capacity to perform an unrelated effortful self-control task. Thus negative transfer between tasks is not necessarily limited to activities that required self-control (Brewer et al., 2011).

Further supporting this, participants chose a higher proportion of chocolate cake compared to fruit after having to remember a 7 digit string compared to a 2 digit string (Shiv & Fedorikhin,1999). In addition, Wright, Stewart and Barnett (2008) extended depletion effects to other cognitive tasks. Participants initially completed a highlighting letters task followed by a 174 word Stroop task or a task containing 254 mathematical problems. Findings revealed that after completion of the initial task, a temporary reduction in performance was observed in both the Stroop and maths task.

Drawing on further evidence in support of general cognitive depletion a study exposed participants to a two-hour period of cognitive exertion, in which multiple tasks requiring complex cognitive ability were performed. After engaging in the cognitive activities, participants produced a weaker performance on the WCST and Tower of Hanoi task but performance in a less demanding task of remembering was not impaired (van der Linden, et al., 2003). Therefore, continuous controlled cognitive processing (top down) adversely affected performance in conscious deliberate control tasks only.

The research evidence thus suggests a possible need to shift away from referring to the adverse impact an initial self-control task has on subsequent exertion, and instead consider the wider implications of completing effortful cognitive tasks in general on other cognitively demanding tasks. And in fact it is evident that there appears to be disagreement in the use of the term 'depletion' in the literature; with some referring to general cognitive depletion or cognitive fatigue when discussing depletion effects. For example, 'cognitive fatigue' (Ackerman & Kanfer, 2009) was defined in a similar way to Baumeister et al.'s (2007) concept of 'ego depletion'; that following continued effort, one's ability to continually exert effort reduces. Thus there is considerable overlap in the way that resource depletion, ego depletion and cognitive fatigue are defined.

Consequently, a further aim of this thesis (paper three; chapter five) was to assess whether the temporary deficiency in performance in the second of two cognitive tasks applies to general cognition or whether it is specific to tasks that rely solely on self-control processes.

Population/Older adults

Studies exploring sequential self-control task performance have predominately relied on the recruitment of younger aged samples of participants; there is a lack of research extending this to older aged adults (Hagger, 2010; Dahm, Neshat-Doost, Golden, Horn, Hagger & Dalgleish, 2011). Generalisation of self-control effects observed in younger populations poses problems, as evidence showed that the frontal brain regions, which support self-control and inhibitory processes, are still undergoing development at this age (Sowell, Thompson, Holmes, Jernigan & Toga, 1999). For example, frontal brain region development and specifically the prefrontal cortex - a crucial area for higher cognitive self-control and inhibitory processing - undergoes maturation until age 20 (Fuster, 2002; Diamond, 2002). Therefore, attempting to study the cognitive processes that are enacted by such brain regions is difficult if one solely uses younger samples of participants from the population.

The few studies that have assessed the relationship between self-control performance over time in a sequential task paradigm and ageing have produced mixed findings, with one extending the depletion effects to older aged adults (Bray, Ginis & Woodgate, 2011) whereas another failed to replicate this finding in older aged adults (Dahm et al., 2011). Further research was therefore required to investigate the effect in different age groups. Thus one aim of this thesis (paper six, see chapter eight) was to explore the relationship between the ability to apply self-control sequentially over time and age.

Thesis aims

Evidence from the literature on self-control showed that exercising self-control following prior self-control exertion poses difficulty. Research proposed that this impairment stemmed from a temporary reduction in the availability of an energy resource, such as glucose (Baumeister et al., 2007; Gailliot et al., 2007); through self-control exertion the availability of glucose diminishes. One of the main aims of this thesis was to extend the existing literature on self-control by adopting a novel more objective measure of self-control (the antisaccade paradigm) and to further elucidate whether energetic resource depletion drives the impairment in self-control and whether glucose administration counteracts these effects. Moreover this thesis also aimed to investigate whether a temporary reduction in self-control following previous exertion is influenced by intrinsic motivation level independent of glucose availability. Further, we aimed to explore whether there are differences in the effects of depletion of subsequent performance depending on whether two identical or to two dissimilar tasks of self-control are performed in close succession. We were also interested in assessing whether trait differences in self-control and/or differences in whether one believes self-control capacity is limited influences self-control performance over time. Addressing a another current gap in the literature, a further aim was to evaluate whether a temporary reduction in self-control performance across two sequential tasks can be extended to older aged adults (Hagger et al., 2010).

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Paper one: The role of Motivation, Glucose and Self-control in the antisaccade task

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RESEARCH ARTICLE

The Role of Motivation, Glucose and Self-Control in the Antisaccade Task

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Abstract

Research shows that self-control is resource limited and there is a gradual weakening in consecutive self-control task performance akin to muscle fatigue. A body of evidence suggests that the resource is glucose and consuming glucose reduces this effect. This study examined the effect of glucose on performance in the antisaccade task - which requires self-control through generating a voluntary eye movement away from a target - following self-control exertion in the Stroop task. The effects of motivation and individual differences in self-control were also explored. In a double-blind design, 67 young healthy adults received a 25g glucose or inert placebo drink. Glucose did not enhance antisaccade performance following self-control exertion in the Stroop task. Motivation however, predicted performance on the antisaccade task; more specifically high motivation ameliorated performance decrements observed after initial self-control exertion. In addition, individuals with high levels of self-control performed better on certain aspects of the antisaccade task after administration of a glucose drink. The results of this study suggest that the antisaccade task might be a powerful paradigm, which could be used as a more objective measure of self-control. Moreover, the results indicate that level of motivation and individual differences in self-control should be taken into account when investigating deficiencies in self-control following prior exertion.

Introduction

Self-control refers to the regulation of behaviour and inhibition of automatic/impulsive actions, for example when suppressing a powerful emotional response to a disturbing experience [1]. When exercised daily, this important psychological process [2] is associated with positive life outcomes, whilst poor self-control is linked to increased social adversity [3]

Self-control requires the conscious and effortful control of actions, and contrasts with more unconscious/automatic forms of cognition [4]. Self-control is also an executive function (EF); a higher-order cognitive process associated with the dorso-lateral-prefrontal cortex (dlPFC) [5]. The activation of the dlPFC during self-control has been well documented using functional-magnetic-resonance imaging (fMRI) [6], with reduced activation during weakened self-control [7].

Several studies have shown that individuals have difficulty completing two consecutive self-control tasks; the first is completed normally, but there is usually a temporary impairment in performance on the second [8]. The resource depletion theory [9] suggests that this impairment stems from a depletion of resources with self-control drawing on a limited supply [10]. The effects are specific to self-control tasks and not found in relatively automatic and effortless tasks [8, 11]. These observations have been strongly supported across over approximately 80 studies using various measures of self-control [3].

One influential line of research suggests that self-control is glucose dependent [1]. Glucose is essential for brain function, and is distributed and metabolized according to areas of activation. It has been suggested that the amount of cognitive effort needed to complete a task moderates the susceptibility to changes in glucose availability, i.e. one factor that appears to be of particular relevance is whether tasks are cognitively demanding [12; 13]. The energy cost for effortful, controlled or executive processes appears to be significantly higher than that for automatic or reflexive processes [14] Indeed, lowered peripheral glucose levels following performance of a cognitively demanding task have been reported [15; 16]. These results indicate that cognitively demanding tasks and in particular those relying on executive functions are sensitive to changes in glucose availability.

A series of experiments explored that relationship with evidence showing that acts of self-control use relatively large amounts of glucose and that glucose administration can improve self-control (see [14] for review). More specifically, it has been shown that blood glucose levels declined following self-control exertion in an incongruent, but not congruent, Stroop task [15]. Weak self-control was reported following a reduction in glucose levels, induced by a previous task, but administration of a glucose load counteracted this [8]. Similarly, selfish desires were more frequently suppressed and there was an increase in offers of support to others, following glucose ingestion [17]. This supports the idea that self-control is weakened when blood glucose levels are low.

Challenges to the resource depletion theory

Research suggests that the role of motivation in moderating one's temporary deficiency in self-control following prior exertion needs to be considered. This idea is captured by the resource allocation account [18], which proposes that high levels of motivation will modulate acts of self-control irrespective of whether or not the individual has been exposed to a previous self-control task. This account acknowledges that engaging in self-control requires glucose, but argues against the strong claims of the resource depletion theory that self-control per se is sufficient to produce a significant diminishment or depletion [18, 19]. The account posits that while engaging in a self-control task, glucose will be assigned based on one's intrinsic level of motivation to complete that task. Thus resources will be allocated if one deems the task to be important [18]. Therefore impaired performance that has typically been documented in a second task of self-control might be associated with how willing or motivated one is to engage in a task rather than—as the resource depletion theory claims—solely dependent on whether or not there is a sufficient resource to complete the task. Self-report measurements have been recommended to determine whether task importance and interest (i.e. intrinsic motivation) can offset the temporary deficiency one observes in the second of two self-control tasks [18].

Recent findings support the resource allocation account and challenge claims made by the resource depletion theory that glucose is significantly depleted during self-control exertion. Molden and colleagues, for example reported no decline in blood glucose after a self-control task was completed [20]. Further, a re-analysis of Gailliot and colleagues research disputes the observation that blood glucose levels significantly are reduced following the application of self-control [19].

Additionally, Sanders and colleagues [21] recently reported that a glucose facilitation effect on self-control was detected after gurgling with (not ingesting) a glucose drink. This evidence suggests that replenishing glucose resources through glucose ingestion may not be necessary to improve self-control and that glucose might exert its beneficial effects on self-control performance in a more indirect way. For example, glucose itself may be motivational and indeed its presence in the mouth stimulates brain areas associated with reward [22]. Framing Sanders and colleagues [21] findings within the resource allocation account, glucose may provide one of several pathways to increase one's level of motivation—alongside the offering of monetary incentives [23] and one having feelings of autonomy towards task engagement [24]—which could then ameliorate the temporary deficiency in performance observed in a second task following the completion of an initial self-control task [18].

Baumeister and colleagues e.g. [25] have recently proposed a revision of their original resource depletion theory by incorporating the resource allocation account [18]. They now propose that motivation would only moderate the level of engagement in a subsequent task of self-control in situations where there is an insufficient level of resources—due to prior self-control engagement—available for further self-control acts.

The aim of this study was to further investigate the role of glucose in self-control and to examine the potential moderating role of motivation. In particular, by monitoring blood glucose levels over time the current study attempted to explore whether any decline in self-control was indeed linked with a significant reduction in peripheral blood glucose availability. A glucose drink was also administered to examine whether relative to placebo, glucose would improve the powers of self-control following exertion in the Stroop task.

Previous research has predominately used behavioural measures of self-control and there is a lack of investigations that have used more objective measures of self-control. One well-established objective measure is the antisaccade task (AST) [26], in which an automatic saccadic eye-movement to the onset of a visual stimulus is suppressed, and a voluntary saccadic eye-movement is elicited away from the stimulus [27]. The AST correlates well with other self-control measures (e.g. the Stroop) [28], and involves the activation of the dlPFC and subcortical networks [27, 29]. In addition, it serves as an implicit indicator of self-control and error awareness, which is measured in terms of the frequency of spontaneous corrections that are generated following an incorrect saccade towards the target. The AST also yields temporal and spatial information, and has been directly linked to inhibitory networks in the brain [30], which could provide a reliable and objective "biomarker" for self-control [3].

In the prosaccade task (PST) the goal is to look directly towards the target, which requires no inhibitory control [31]. The AST, together with this control task, would determine whether glucose administration influenced the general properties of saccadic eye-movements or more specifically, only those under self-control. Prosaccade (PS) responses are 100ms faster and produce less errors than antisaccade (AS) responses [29, 32]. We predicted a task that demanded strong self-control would impair subsequent AS (but not PS) performance and that supplementary glucose and/or level of motivation would attenuate this.

The study also examined the potential moderating effects of individual differences in self-control on saccade performance. We predicted—based on previous research—that poor levels of self-control would be linked with a larger decline in AS (but not PS) performance following self-control exertion [33, 34].

Overall, evidence has shown that consecutive self-control tasks lead to weakened performance levels in these tasks, and that supplementary glucose helps to restore control [14]. However, recent evidence is beginning to challenge the role of glucose in self-control. Consequently, this study employed a frequently used initial 'depletion' task (the incongruent Stroop) [3] to determine whether a temporary resource deficiency was responsible for the decline in subsequent performance of a novel more objective measure of self-control (the AST) and whether a glucose drink would restore performance. Both measures of self-control that were employed—the Stroop task and AST—required one to exert self-control by responding to an external prompt, for example a signal or instruction rather than relying on self-control, generated based on one's personal intentions or decisions [35]. The research also addressed whether levels of motivation and individual differences in self control moderate the effects of depletion.

Materials and Methods

Research design

To examine the effects of glucose (vs. placebo) administration on self-control performance, the experiment used a double-blind placebo controlled, 2 (drink condition: glucose, placebo) x 2 (saccade task: PS, AS) mixed-factorial design with repeated measures on the second factor. Participants were randomly assigned to drink condition.

Participants

Seventy one undergraduate and postgraduate students of Lancaster University participated voluntarily or in exchange for course credit. Four were excluded from the analysis due to their AS performance indicating that they failed to fully understand the task instructions. This resulted in a final sample of 67 participants (48 female, 19 male) aged between 18 and 38 years of age (*M* age = 21.15 years). This sample size was based on the previous literature which have shown clear effects of glucose deficiency on self-control (see three studies reported in [8] which employed sample sizes of 16, 12, and 24). The sample size was chosen to be in excess of those used previously (see [8]). Further, a power analysis calculation was conducted based on previous findings, which indicated that with an alpha level of. 05, a sample size of 67 would be sufficiently highly powered (.78) according to Cohen's standards [36]. Potential participants were excluded on grounds of the following: diabetes mellitus (and/or history of the illness); any glucose intolerances; pregnancy, lactating. Ethical approval was granted by the Lancaster University Ethics Committee and all participants completed a form detailing their written consent with the right to withdraw before commencing the study.

Materials

Initial measure of self-control: Stroop task. A computerised version of a frequently used incongruent Stroop task (colour words and ink colours were mismatched), containing 135 colour words (red, blue, green, yellow or purple) was administered [37]. Each word was presented for 2,000 ms and participants were instructed to respond to the ink colour of the word as precisely and as rapidly as possible by pressing particular keys on a QWERTY keyboard ('P' for purple, 'Y' for yellow, 'G' for green, 'B' for blue and 'R' for red) and to say aloud the ink colour. For words presented in red ink only, the word itself was to be read rather than the ink colour.

Self- control scale [38]. The full 36-item self-control scale was administered to assess individual differences in self-control. Each item was rated using a 5-point-Likert scale (1 = '*not at all like me*' to 5 = '*very much like me*') providing an overall score.

Intrinsic Motivation Inventory (IMI) [39, 40]. Responding to the resource allocation account and the need to consider motivation [18], participants' self-reported level of intrinsic motivation was examined using a 36 item IMI. Responses were made on a 7-point-Likert scale ranging from '*not at all true*' to '*very true*'. Example statements, which required a response

Table 1. Drink composition.

Glucose	Placebo
25g glucose (dextrose) powder (Thornton & Ross Ltd, Huddersfield, HD7 5QH), 10ml lemon juice, 250ml cold water	5 Saccharin tablets (Sweetex, Reckitt Benckiser PLC, Slough, SL1 3UK, UK), 10ml lemon juice, 250ml cold water

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included, 'I enjoyed doing this activity very much', 'This activity was fun to do', 'I did this activity because I wanted to' and 'I would be willing to do this again because it has some value to me'. The items were summated to give an indication of how motivated participants were to complete the tasks, which they performed [41].

Saccade tasks [26]. Participants were seated with their head positioned on a chin rest located 57 cm from a 19″ monitor on which the visual task was displayed. An Eyelink 1000 (SR Research: 1,000 Hz, <.5° accuracy) was used to record response times of saccades towards the target. In both tasks, a fixation cross appeared in the centre of the screen. After 1,000 ms, a small green circle (.6° diameter) appeared 8° to the left or to the right of the cross. The target and cross remained on the screen for 1,000 ms, and a 1,500-ms interval preceded the next trial. The location of the target was randomised and appeared on the left or right with equal frequency. Participants were instructed to direct their eyes towards the circle (PST) or away—and to the opposite side of the circle (AST) as quickly and as accurately as possible. Two specific saccade parameters—reaction times (latencies in milliseconds; ms) and the frequency (%) of directional errors—were measured in order to compare potential performance differences in the PST and AST.

Blood glucose levels. Measured at baseline (time 1), after Stroop task completion (time 2) and after both the PST and the AST were administered (time 3) with the Exactech measuring equipment (supplied by Medisense Britain Ltd), according to the manufacturers' guidelines. Akin to those used by individuals with diabetes mellitus, this portable finger-prick glucose monitoring device provides a reliable measure of blood glucose [42]. Further, a recent study found a strong correlation between capillary blood glucose measures (finger prick) and AV blood [43], confirming its measurement sensitivity.

Sensory Evaluation Form [44]. Participants rated how much they liked the drink across five categories on a 9-point Likert measure (1 = '*like extremely*' to 9 = '*dislike extremely*').

Drinks. A glucose or inert placebo drink, matched for sweetness and flavoured with lemon juice were randomly administered in transparent plastic cups, at room temperature, following a double-blind procedure (see Table 1 for drink compositions). Sensory evaluation revealed that the glucose and placebo drinks were liked equally ($F(1, 66) = .59$, $p = .45$).

Procedure

Each participant attended one testing session (approximately 50 minutes). Prior to testing, participants were provided with information about the study and asked not to consume anything except water for at least two hours and refrain from consuming any alcohol for at least 12 hours before the session.

On arrival, participants were given an information sheet and gave informed consent and demographic information. For each task, full instructions were provided. At the beginning of testing, participants' baseline blood glucose levels were measured (time 1). Participants then completed the computerised Stroop task (which lasted approximately four minutes, thirty three seconds) followed by a second blood glucose reading (time 2) and the double-blind administration of the glucose/placebo drinks. Participants evaluated the overall likeness for the drink using the sensory-evaluation form [44] and then completed the self-control questionnaire [38]. Participants were then seated in front of the eye-tracking computer and the headset and saccade tasks were prepared. Fifteen minutes following drink administration (allowing for glucose absorption), the saccade tasks were conducted over an approximate 6 minute period. During this time participants were instructed to remain as still and as relaxed as possible to ensure that accurate readings were taken. The PST was administered first, followed by the AST, due to evidence of carry over effects from the AST [45]. A final blood glucose reading was recorded (time 3) after completing the saccade tasks. The IMI [39; 40] was then administered before participants were fully debriefed.

Statistical analysis

Saccade latencies (saccade reaction times; RTs) were computed as the delay between target onset and the start of the first saccade, with an amplitude of greater than 2°. Responses of less than 80 ms or over 500 ms were regarded as anticipatory or late saccades, respectively, and were excluded from analysis. For directional errors, the total number of errors (incorrect saccades made towards rather than away from the target) in the AST was obtained and then converted to a percentage error rate based on the number of trials completed for each participant.

Initially, a correlational analysis on the overall data was conducted. Following this, using IBM SPSS Statistics Version 20, saccade performance was analysed using mixed-effects modelling. Specifically, we ran through a series of separate models for the two measures of performance in the saccade tasks; reaction times (RTs) and AST directional error rate (with F values drawn from '*Type III Tests of Fixed Effects*'). In the models, participants were included as random effects and task type for saccade RTs as well as drink condition were included as fixed effects. Self-reported levels of both motivation and self-control were added as covariates to the models to assess whether differences in motivation and self-control moderated drink effects on saccade performance (reaction times and/or directional errors) or whether they were significant predictors of performance irrespective of drink condition. Similarly, glycaemic response was analysed using mixed effects modelling, again treating participants as random effects and both drink condition and time (T1: baseline, T2: post Stroop task completion and T3: post drink and saccade task performance) as fixed effects. Self-reported levels of motivation were also added as a covariate to the model to assess whether differences in motivation was a significant predictor of glycaemic response.

Results

Correlations

As demonstrated in Table 2, the correlational analyses revealed a significant negative relationship between motivation and directional error rate in the antisaccade task; those high in motivation produced fewer errors in the AST. Additionally PS RTs were significantly positively correlated with AS RTs; longer responses in the PST were paired with longer response times in the AST. Further, the correlation analysis revealed a negative relationship between PS RTs and error rate in the AST; faster PS responses were paired with more erroneous responses in the AST.

Drink condition effects (glucose vs placebo)

Blood glucose levels. There was a significant effect of time ($F(2, 71.59) = 52.99$, $p = .00$) and of drink condition ($F(1, 68.46) = 64.10$, $p = .00$) and a significant time x drink condition interaction ($F(2, 71.86) = 49.32$; $p = .00$). Further post-hoc analyses for the interaction revealed

Table 2. Correlation matrix.

Variable	1	2	3	4	5
1.Motivation	——	.123	.005	-.220	-.385**
2. Self-control		——	.144	.071	.042
3. Prosaccade RT			——	.325**	-.252*
4. Antisaccade RT				——	.110
5. Antisaccade directional error rate					——

Note. ** p <. 01,
* p <. 05, RT = response times

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that following glucose administration (time 3), blood glucose levels were significantly higher compared to times 1 and 2 (p = .00) and all blood glucose levels following placebo (all p<.01; see Fig 1 created in R, Version 0.98.501). No significant differences in blood glucose levels over time were detected following placebo administration. Specifically, no significant reduction in blood glucose levels from baseline was observed after Stroop task completion (time 2; p = .96).

Saccade Performance. Initially the model was fitted to account for both participants as random effects and task type as a fixed effect. This analysis revealed a significant relationship between saccade RTs and task type (β = 63.13, t (66) = 11.61, p <. 001). There was a significant effect of saccade condition on RTs (F (1, 67) = 136.88, p = .00); PS RTs (M = 200.99,

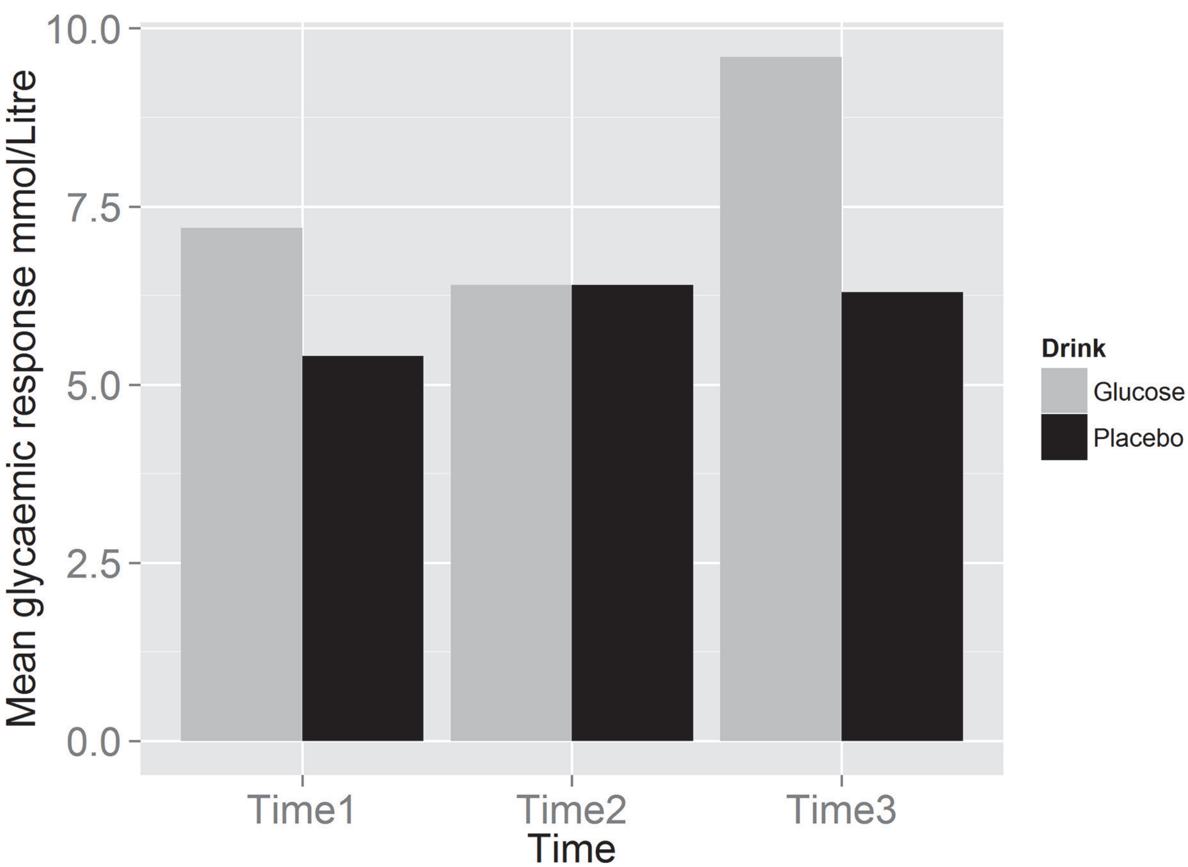

Fig 1. Mean (±95% confidence intervals) blood glucose level measurements over time as a function of drink condition.

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SD = 36.72) were significantly faster than AS RTs (*M* = 264.13, *SD* = 39.76). We then added drink condition and the interaction between drink and task type as fixed effects to the model. There was no effect of drink condition (F (1, 67) = 0.38, p = .54) or a task x drink condition interaction (F (1, 67) = 0.80, p = .37) on saccade RTs. Moreover, for directional errors, the initial model with drink condition as a fixed effect and participants as random effects showed drink condition to not be a significant predictor of AS directional error rate. (F (1, 65) = .00, p = .96).

Intrinsic Motivation and Individual differences in self-control reported using the self-control scale [32]

We initially checked whether there were differences in motivation and self-control by drink condition. There was no significant differences in levels of motivation following the glucose and placebo drinks (F (1, 66) = .04, p = .84); nor were there any significant differences in reported self-control between groups (F (1, 66) = .56, p = .46). Adding motivation and self-control to the model did not result in significant drink effects on saccade RTs (F (1, 67) = 0.63, p = .80) or directional errors (F (1, 63) = .002; p = .96). Moreover, the task x motivation interaction failed to reach significance for saccade RTs, (F (1, 67) = 2.92; p = .09) and further inspection revealed that higher motivation did not significantly predict AS RTs (β = -14.49, t (65) = -1.65; p = .10) (see Fig 2; created in R, Version 0.98.501). In addition no significant task x self-control interaction was observed on saccade RTs (F (1, 65) = .20, p = .65).

However, interestingly adding motivation to the model showed that motivation itself was a significant predictor of frequency of directional errors, irrespective of drink condition (F (1,

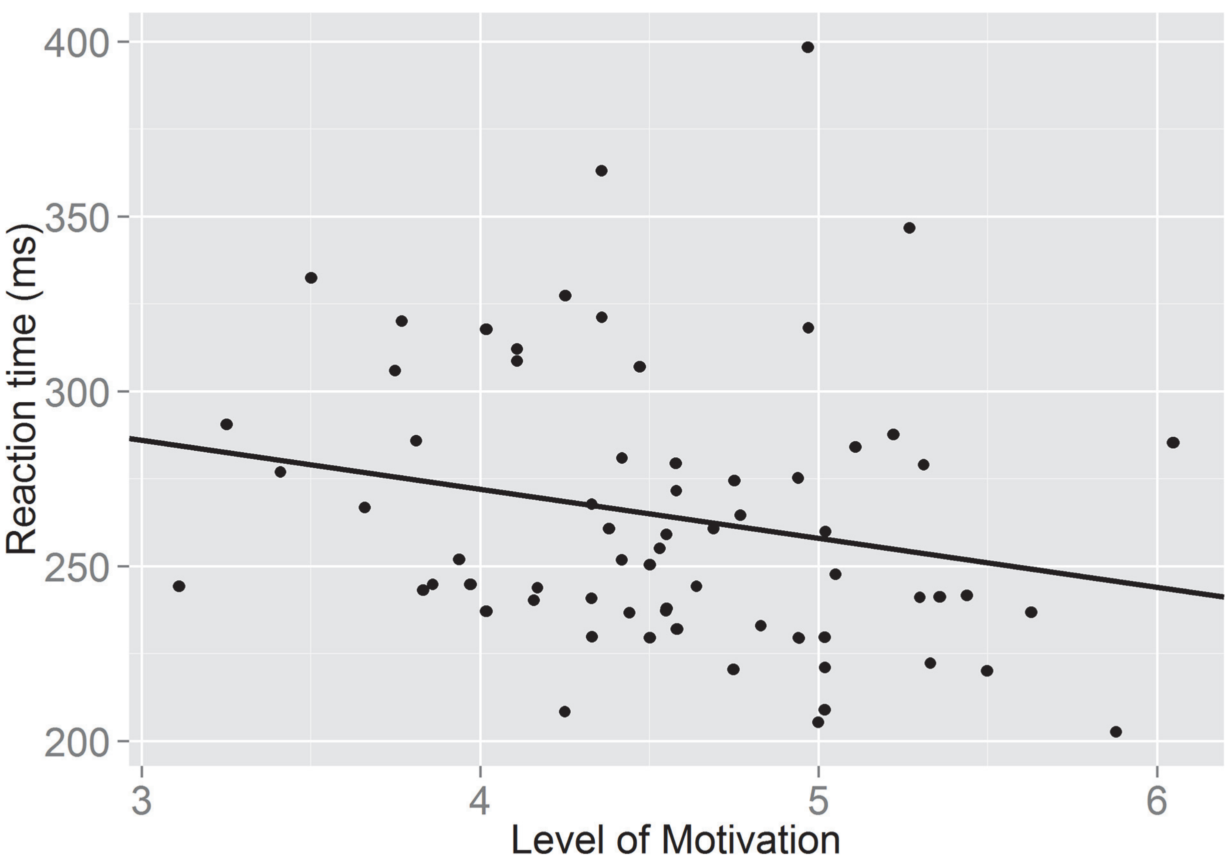

Fig 2. A graph showing the relationship between self-reported level of motivation and speed of responding in the antisaccade task.

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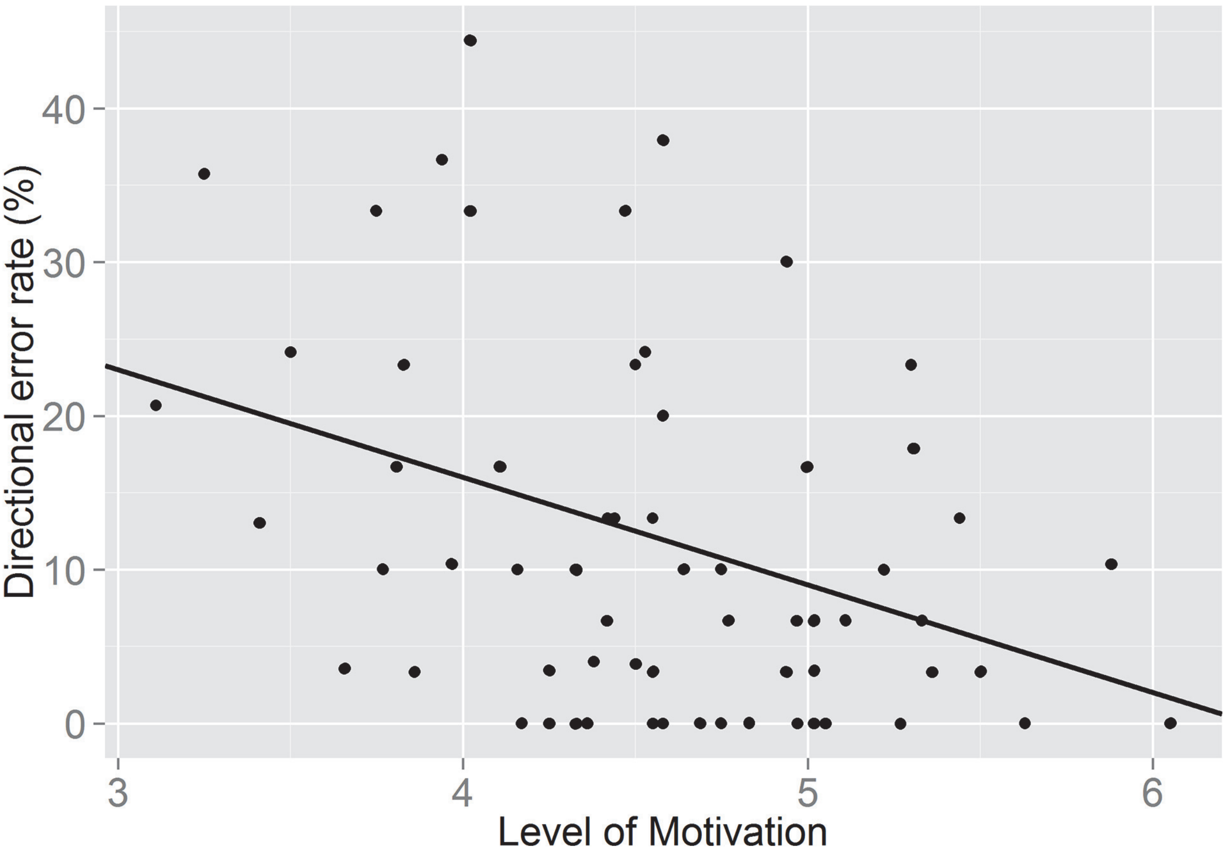

Fig 3. A graph showing the relationship between self-reported level of motivation and directional error rate in the antisaccade task.

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63) = 11.53; p = .001) The relationship between directional error rate and motivation was negative (β = - 7.42, t (63) = - 3.395, p = .001), indicating that higher motivation resulted in fewer errors being committed in the AST (see Fig 3; created in R, Version 0.98.501). These results show that when taking into account the amount of self-reported motivation to perform the second self-control task, the type of drink consumed does not become a significant predictor of task performance. However, motivation itself appears to be a better predictor of task performance. Individual differences in self-control did not predict errors on the antisaccade task (F (1, 61) = .581, p = .449), however there was a significant drink x self-control interaction (F (1, 61) = 4.074; p = .048). For those consuming the glucose drink, levels of intrinsic self-control predicted frequency on the number of directional errors, with higher levels of self-control resulting in fewer errors (β = -.308, t (61) = -2.018; p = .04).

We also evaluated the effect of motivation on blood glucose levels, as these might be affected by level of motivation due to potential differences in neuroendocrine activation. However, addition of motivation as a covariate to the model did not change the previously observed main effect or interaction. In addition, motivation itself did not significantly predict blood glucose levels (F (1, 63.48) = 1.66; p = .20).

Discussion

The resource depletion theory argues that self-control is resource limited and has been supported with evidence that two successive self-control tasks yield a decline in self-control in the second task [1; 3]. It has been suggested that glucose is the major resource for self-control and that administration of a glucose load can reduce the temporary deficiency in performance in a second task of self-control [8]. In the current study administration of a glucose drink was expected to enhance performance in the AST in comparison to placebo following self-control exertion in the Stroop task. This prediction was not supported, and therefore failed to replicate previous research e.g. [8, 17].

However, our findings revealed a strong effect of motivation on self-control. Level of motivation was a significant predictor of directional errors in the AST, suggesting that higher levels of self-reported motivation were related to the production of fewer errors in the task. However, low levels of self-reported motivation resulted in a greater number of directional errors in the AST, which is indicative of self-control failure. These observations provide support for the resource allocation account [18], as low levels of self-reported motivation to complete the AST produced the expected deficiency in self-control performance—greater errors—following prior engagement of self-control in the Stroop task. Further, although there was a trend to suggest that level of motivation was a predictor of AST response speed, which is supportive of the resource allocation account that motivation has an ameliorating effect on the temporary deficiency in subsequent self-control performance [18], this observation was not significant.

Previous work [31] has shown, faster saccadic reaction times are associated with a higher AST error rate. In the current study, the weak correlation between AS reaction times and motivation suggests that the relationship between motivation and directional error rate is not mediated by effects on reaction time. These data would therefore imply that motivation is not exerting its effect on error rate via this route, but that motivation might be having a more direct effect on AS error rates. This provides stronger supportive evidence for the role of motivation in alleviating the temporary deficiency in AST performance following prior self-control exertion.

No effect of motivation levels were observed in the PST, which required no inhibitory control, suggesting that prior self-control exertion did not influence the general properties of saccades. It is worth noting that previous research has found that the effects a self-control task has on subsequent exertion are quite specific. Tasks pertaining to self-control, not general cognitive measures, are diminished following self-control exertion [11]. Here, motivation level did not significantly predict performance outcome in the PST, this finding was thus unique to the AST, which required effortful cognitive control.

In line with previous research e.g. [20; 21] no significant decline in peripheral glucose levels was observed after the Stroop task. It has previously been argued that the failure to observe a drop in peripheral glucose levels after performing a self-control task challenges the resource component of the resource depletion theory, specifically the notion that an energy substrate like glucose is depleted during self-control exertion [19]. However, it is important to note that the failure to observe a decline in peripheral blood glucose levels does not necessarily mean that there is no temporary shortage in energy supply centrally. For one, it has been argued that the glucose measuring devices used in this study and previous research (e.g. [15; 8]) may lack sensitivity to detect such subtle reductions in glucose levels [18; 19]. Moreover, changes in peripheral levels do not necessarily equate to changes in the level of glucose in the brain [19].

Although evidence suggests that brain glucose levels are approximately 15–20% of blood levels [46; 47; 48; 49; 50], glucose metabolism varies throughout tissue and cell type in the brain. Both the rate of blood to brain glucose transport [51] and glucose metabolism [52] are stimulated in different areas in the brain during cognitive tasks relevant to that area. There is disagreement about the additional energy costs associated with task performance, ranging from as little as 0.5% to 1.0% of the total energy budget [53] to evidence suggesting that performing cognitively demanding tasks increases total brain consumption by as much as 12% [54]. However, regardless of the actual level of additional cost, it takes approximately four to six seconds following neural activation for blood flow to increase, which suggests a temporary energy shortage in neurons may occur [53]. This (temporary) insufficiency has been suggested to underlie the improvement effect of glucose ingestion upon cognition [55]. Microdialysis measurements of brain glucose have shown a large decrease in hippocampal extra cellular fluid (ECF; 32 ± 2%) in rats tested for spontaneous alternation on a four-arm maze (a difficult memory task), while a smaller decrease (11 ± 2%) was seen in rats tested on a simpler three arm-maze, suggesting that the changes observed in ECF glucose are related to task difficulty. Moreover, there is some evidence that the concentration of ECF glucose in the brain after its transfer across the blood-brain barrier from plasma glucose varies with brain region (for review, see [56]). The cerebral cortex has comparatively low stores of glycogen (5–6 mmol/l compared to for example 13 mmol/l in the hippocampus [57]) suggesting that it might be particularly sensitive to those temporary deficits. Consequently, the failure to observe a significant decline in peripheral blood glucose levels after the initial self-control task [20], does not necessarily imply that there are no slight alterations in glucose levels following completion [19] and thus that exerting self-control does not rely on the availability of glucose.

Although we observed a powerful effect of motivation and reported no effect of glucose on self-control performance this also does not mean that the limited resource view of self-control should be dismissed. What these observations do reinforce however, are trends that have recently emerged in the self-control literature, i.e., that a reconsideration of the resource model is perhaps needed [19] with additional factors taken into account. As mentioned earlier, Baumeister and colleagues [25] have suggested possible amendments to the resource depletion theory, which acknowledges the resource allocation account [18] and the moderating effects of motivation. In particular it has been argued that motivation can counteract the temporary deficiency in self-control following prior exertion when glucose resource levels are low [25].

The current findings together with previous evidence therefore suggest that motivation might be an important factor in the temporary deficiency in self-control one observes in a subsequent task following exertion. More broadly, self-control performance and more specifically the degree to which it is affected by glucose availability, appears to be influenced by individuals' motivation to exert self-control.

According to one interpretation, glucose might be motivational, thus stimulating reward areas in the brain [22]. For example self-control performance improved for participants that simply gurgled with glucose (not placebo) before a second task of self-control was completed [21]. The current study did not detect such an effect on motivation with the glucose drink and supports more recent evidence which reported no effect of glucose whether swilled or digested on self-control ability after prior exertion [58]. The neurobiological mechanisms underlying the observed moderating effects of motivation need to be explored. However, it is feasible to speculate that the motivation reported by participants may result or indicate a brief acute stress response mediated by sympatho-adrenomedullary axis (SAM axis) activation. Indeed, it has been argued that the importance of a task determines the initial preparedness via activation of one or both major endocrine systems, the hypothalamic-anterior pituitary-adrenocortical axis (HPA) and the SAM axis [59]. A major physiological role of activation of both endocrine systems is considered to be a temporary increase in energy production and more specifically provision of additional metabolic fuel through increase in glucose availability [60]. Consequently, in physiological terms motivation to perform a task, could lead to an intrinsic rise in glucose availability which in turn ameliorates any potential energy shortage. In the current study, motivation did not appear to change blood glucose levels. However, as these changes would arguably be very small, these might not have been detected due to lack of sensitivity of the measuring device. Alternatively, differences in motivation might affect performance through selective allocation of available resources; i.e. resources are channelled to areas of the brain pertaining to tasks that are seen as sufficiently important.

Another interesting finding emerged from analysis of the moderating effects of individual differences in self-control on subsequent performance. Individuals higher in self-reported levels of self-control performed the AST with greater accuracy following glucose consumption than those lower in self-control. This is interesting and requires further exploration, as it is somewhat incongruent with the resource depletion account. In particular one would expect that those low in self-control to be more susceptible to consumption of glucose than those high in self-control due to a greater vulnerability to resource depletion [3]. In the current study the opposite was observed.

This is the first study to investigate the effect of completing an initial self-control task on performance in the AST. The results of our study suggest the AST as a promising objective task of self-control, which can be simply administered [29] and compared to previous measures, assesses self-regulation on an implicit level by recording saccades that correct directional errors. It also uses the single modality of vision for both processing the stimulus and the behavioural response, in contrast to previous methodologies, where the stimulus was encoded for example visually, but an auditory or motor response was required. This modality task switching limited the extent to which self-control could previously be directly assessed [61].

Consequently, the findings have helped to address a particular problem inherent in the existing research field on self-control, which is the current difficulty in finding congruency in the measurement of self-control [3]. A wide range of tasks have been used to study the effects of a temporary deficiency in self-control ability [62]. Moreover, evidence linking glucose administration as well as the moderating effects of motivation and self-control to cognitive functions associated with restraint and willpower have not been validated using "biomarkers" of self-control. The results of this study demonstrated that implementation of the more objective AST as a measure of self-control within a self-control depletion paradigm is feasible.

Although our observations are reflective of more recent studies, it is important to note that in comparison to previous studies on self-control, the dose of glucose administered in the current study was lower (25g) compared to studies which showed beneficial effects with larger (35-40g) doses (e.g. in [8] and [17]). The effect of glucose administration on cognitive tasks, including memory follows an inverted U-shaped dose response curve [63; 64]. Although, the dose we used has previously shown to be optimal for facilitation of memory performance, it might be the case that a higher dose is needed to facilitate tasks pertaining to frontal lobe functions. Thus, further investigations are clearly required to determine the dose-response relationship between glucose, self-control performance and levels of motivation.

A further limitation of the current study that needs to be addressed by future research would be the more specific assessment of the ameliorating effects of motivation on self-control performance. This could be done by manipulating levels of task motivation rather than recording overall task motivation.

Conclusion

In summary, the results of the current study suggest the AST could be a potential 'biomarker' of self-control and thus a powerful paradigm to use in future studies on self-control. Moreover, the study did provide further support for the resource allocation model, as motivation—specifically, how personally relevant it was to participants to complete the task—influenced self-control performance more powerfully than glucose administration. More specifically, higher motivation appeared to ameliorate the temporary deficiency in a self-control task, as participants with low motivation produced a weaker AS performance following self-control exertion.

More research is needed to explore the role of factors (including motivation and self-control) that can act as response modifiers and neuroendocrine mechanisms should also be evaluated as a potential source for variability.

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Author Contributions

Conceived and designed the experiments: CLK SIS TJC. Performed the experiments: CLK. Analyzed the data: CLK SIS. Contributed reagents/materials/analysis tools: CLK SIS TJC. Wrote the paper: CLK SIS TJC.

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Paper Two: The sequential completion of identical compared to dissimilar self-control tasks and the modulating effects of high cognitive effort and intrinsic motivation on subsequent self-control performance

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Abstract

The robustness of the ego depletion effect (after the initial application of self-control, a temporary deterioration in subsequent self-control performance occurs) has been debated, with recent evidence failing to replicate this response. In series of pilot studies (total N = 126 participants; N per study = 18) were conducted, employing combinations of three different tasks - Stroop, antisaccade and attention control video tasks – to further examine ego depletion and the potential factors that might modulate sequential self-control task performance. The novel implementation of the antisaccade task into a sequential self-control task design – paired with two frequently used tasks - assessed its' employability as a biomarker for the measurement of self-control. Two studies administered two identical sequential self-control tasks, and examined whether a reduction in self-control ability was unique to dissimilar tasks or whether it extended to similar tasks. The completion of the control and self-control versions of the initial tasks, were compared to dual-task administration. The moderating effects of intrinsic motivation level and trait self-control on sequential self-control performance were also investigated. Findings revealed a reduction in self-control ability following completion of two identical tasks, with impairments more consistently observed when similar tasks were employed. In addition, evidence that motivation predicts subsequent self-control performance was observed; those high in motivation displayed an enhanced performance. The current findings highlight the factors that might moderate successful self-control performance and further questions the tenability of the ego depletion effect.

Key words: self-control, identical, dissimilar, dual-task, motivation

The sequential completion of identical compared to dissimilar self-control tasks and the modulating effects of high cognitive effort and intrinsic motivation on subsequent self-control performance

Self-control can be defined as the ability needed to override one habitual or dominant response for another, for example suppressing certain emotions such as anger in public (Baumeister, Vohs & Tice, 2007). The ability is vital for human social interaction and is used regularly in daily life (Hoffman, Baumeister, Foerster, & Vohs, 2012). Self-control failure however is quite common, for example poor self-control can be associated with societal issues such as obesity, crime, drug abuse. Self-control failure also occurs more generally, for example when faced with completing two sequential self-control tasks, evidence showed that individuals performed the first task well but displayed a temporary impairment in performance in the second (Hagger, Wood, Stiff & Chatzisarantis, 2010). This finding has been replicated widely, with studies administering two sequential self-control tasks and comparing performance in the second task to a group that completed an initial control task that did not require self-control (Hagger et al., 2010). Despite self-control being an important and frequently used ability (Hoffman et al., 2012), a temporary waning in self-control ability thus appears to be a robust and frequent finding (Hagger et al., 2010).

The strength model of self-control/resource depletion theory (Baumeister et al., 2007) posited that self-control impairment stemmed from a reduction in the availability of limited resources. Resources are used during the application of self-control, with fewer resources then available for further self-control exertion resulting in a temporary impairment in subsequent self-control performance. This deterioration in self-control was defined by Baumeister et al. (2007) as ‘ego depletion’. Glucose was proposed as the resource responsible for self-control, with studies finding that initially exerting self-control produced a significant reduction in peripheral blood glucose levels and a glucose (versus placebo) drink restored performance in the second of two sequential self-control tasks (Gailliot et al., 2007; Fairclough & Houston, 2004). Recent research however disputed this reporting no direct link between blood glucose availability and self-control performance (Kurzban, 2010; Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012; Boyle, Lawton, Allen, Croden, Smith, & Dye,2016; Dang, 2016). Although appealing, findings show that the amount of energy consumed by the brain during a cognitive control task (like self-control) is very subtle (Raichle & Mintun, 2006) and thus it is difficult to relate this to the argument that exerting self-control significantly reduces blood glucose levels.

Alternatively, evidence suggests that motivation level rather than glucose modulates self-control performance (Dang, 2016). Research showed that with high levels of intrinsic or extrinsic motivation, performance in a second task of self-control was restored after prior exertion (Muraven & Slessareva, 2003; Kelly, Sünram-Lea, Crawford, 2015; Kazén, Kuhl & Leicht, 2014). The resource allocation account (Beedie & Lane, 2012) for example posited that a temporary impairment in subsequent self-control performance stemmed not from resource depletion but from a reluctance to allocate resources to a task based on a lowering in motivation. The current investigation aimed to further explore the effect of intrinsic motivation level on sequential self-control task performance.

Moreover, research evidence has questioned the robustness of ‘ego depletion’ i.e. that a temporary deficiency in self-control performance occurs following the completion of an initial self-control task (Evans, Boggero & Segerstrom, 2015; Lurquin Michaelson, Barker, Gustavson, von Bastian, Carruth, & Miyake, 2016; Lee, Chatzisarantis, & Hagger, 2016; Carter, Kofler, Forster, & McCullough,2015; Carter & McCullough, 2014). Although a meta-analysis (see Hagger et al., 2010) with over 80 studies supported the observation that a temporary impairment in performance occurs in the second of two sequential self-control tasks, a more recent meta-analysis argued against the strength of this claim (Carter, et al., 2015). Additionally, a large scale replication study with 23 laboratories failed to observe any ego depletion effects (Hagger, Chatzisarantis, Alberts, Anggono, Batailler, Birt & Zwienenberg, 2015). Further investigations – like this - are thus useful in order to supplement the ongoing debate about the nature of self-control failure and the situations in which self-control ability appears to temporarily wane over time (Lee et al., 2016; Dang, 2016).

Some have questioned whether a reduction in self-control performance over time applies to the sequential completion of two identical self-control tasks; research has predominantly relied on the administration of dissimilar self-control tasks (Hagger, et al., 2010). Lange (2015) argued that the strength of the resource depletion theory (Baumeister et al., 2007) would be threatened if it only applied to the completion of different tasks, as one would predict that completing two sequential tasks - irrespective of whether the tasks were identical - would produce a temporary deficiency in performance in the second task. The current study aimed to assess this by administering two identical as well as two dissimilar sequential self-control tasks.

Alternatively, the conflict monitoring theory (Botvinick, Braver, Barch, Carter & Cohen, 2001), posits that a diminished performance would only occur if the two tasks differed. An impaired performance following prior self-control exertion, arguably illustrates the challenge of attending to and altering how one responds to support the required format of the different task. For example research evidence has shown that when completing two of the same tasks in a sequential order, no impairment in performance in the second task is observed (Dewitte, Bruyneel & Gerskens, 2009; Dang, Xiao & Dewitte, 2014).

Further, examining the previous literature, few studies had attempted to manipulate the difficulty of the initial self-control task. Responding to this, we implemented a third initial task, which was a dual task, that relied on both working memory and self-control ability; the self-control task was paired with a serial 15's counting task. We were interested in observing – as the resource depletion theory (Baumeister et al., 2007) would predict - whether completing both tasks concurrently i.e. increasing the cognitive load, would temporarily impair subsequent self-control performance to a greater extent than completing the initial self-control task in isolation. Alternatively, Tuk, Zhang and Sweldons (2015) observed that completing two tasks at the same time led to an improved performance in a subsequent task of self-control, supporting a facilitation effect (Hagger et al., 2015; Converse & DeShon, 2009; Dewitte, et al., 2009). This would suggest that completing cognitively effortful tasks allows adaptation to the task demands which in turn leads to an improvement in subsequent performance. We therefore explored these two competing views, i.e. impairment versus an improvement in subsequent self-control performance following dual task completion.

Further, some have questioned the way self-control has been operationalised in the literature and the fact that a wide variety of self-control tasks have previously been used to assess sequential self-control performance (Hagger et al., 2015; Lurquin et al., 2016). Frequently used measures of self-control include the erasing letters, Stroop, thought suppression tasks, which tap two modalities; one modality processes the information, the other executes the task (Luna, Garver, Urban, Lazar & Sweeney, 2004). To address this concern, we incorporated a more objective task that relied on one modality - to process the information and perform the response - as an alternative measure of self-control; the antisaccade task (Hallett, 1978). We aimed to administer the antisaccade task within a sequential self-control depletion paradigm to observe whether this 'purer' measure would produce similar findings i.e. a temporary deterioration in self-control performance in the second task following prior exertion.

As the implementation of the antisaccade task into a sequential self-control task design was novel, the current study compared its' application with two other tasks – an attention control video task and Stroop task (Stroop, 1935; Hagger et al., 2010) - that have been used frequently within the literature. The current study implemented the antisaccade task as both a dependent measure of self-control and as a depleting (initial self-control) task. Although it was not possible to ‘catch up’ with the literature in this investigation with the antisaccade compared to other tasks such as the Stroop task – which has been heavily employed as both the depleting and dependent measure of self-control (Hagger et al., 2010) – the current investigation aimed to at least provide a partial insight into the feasibility of implementing the antisaccade task into a sequential self-control task design.

In summary, across seven pilot studies we explored whether we could replicate the finding with the administration of two similar tasks that initial self-control exertion temporarily impairs subsequent performance, which has been frequently observed with the sequential administration of two dissimilar tasks (Hagger et al., 2010). The robustness of the ego depletion effect is under debate (Hagger et al., 2015) and therefore the current investigation aimed to explore the factors that might modulate successful self-control exertion. We observed whether making the initial self-control task more cognitively demanding would adversely affect subsequent performance to a greater extent than completing the self-control task in isolation, as the resource depletion theory (Baumeister et al., 2007) posits, or whether a facilitation effect occurs, with an improved performance (Dang, 2016). We also explored – as more recent findings show – whether intrinsic motivation plays a key role in successful self-control performance. Incorporating the antisaccade task into a sequential self-control task paradigm was relatively novel and we wanted to observe whether the earlier findings of a temporary deterioration in self-control performance following prior exertion would extend to this task. Thus employing the antisaccade task as one of the tasks, allowed the assessment of its’ feasible implementation into a sequential task paradigm and whether it could potentially be employed as a biomarker of self-control.

Method

Participants and design

Across seven studies, 126 participants (18 per study) were recruited. Participants either volunteered or received partial credit as part of their Psychology course for taking part. Each study employed a between-subjects design to compare the effect of initial task completion on subsequent performance following a basic cognitive (control) task, a self-control (depletion) task and a dual task (high depletion).

Materials

Attention control video task*:* A six minute 30 second video was presented to participants (without sound), which displayed a female speaking on the left hand side and a sequential list of words presented on the right hand side of the screen.

Control task: Participants were instructed to watch the video clip as they would normally watch a television programme.

Self-control task: Participants were instructed to watch the video clip but focus their attention only on the female speaking and to ignore the words.

Stroop task: A computerised Stroop task containing 135 colour (Purple, Red, Blue, Green & Yellow) words was administered. Participants had to respond to the ink colour of the word as precisely and as rapidly as possible by pressing certain keys on the keyboard.

Control (congruent)*:* Colour words were matched to the ink colour they were written in.

Self-control: This was an incongruent colour-naming task in which colour words and the ink colours of the words were mismatched. Drawing on Wallace and Baumeister's (2002) version, for some of the trials however when the word was presented in red ink, participants were instructed to ignore the rule and respond to the word rather than its' ink colour.

Saccade tasks (Hallett, 1978; see figure 1): Participants completed a series of trials in which a green dot was presented on a computer screen and eye-movements were recorded via a camera (Eye link II) attached to a headset, which the participants wore while they placed their head comfortably on an adjustable chin rest.

Prosaccade (control)*:* Participants were instructed to direct their eyes towards the green target.

Antisaccade (Self-control/depletion)*:* Participants were instructed to direct their eyes away - and to the opposite side of the screen – from the green target.

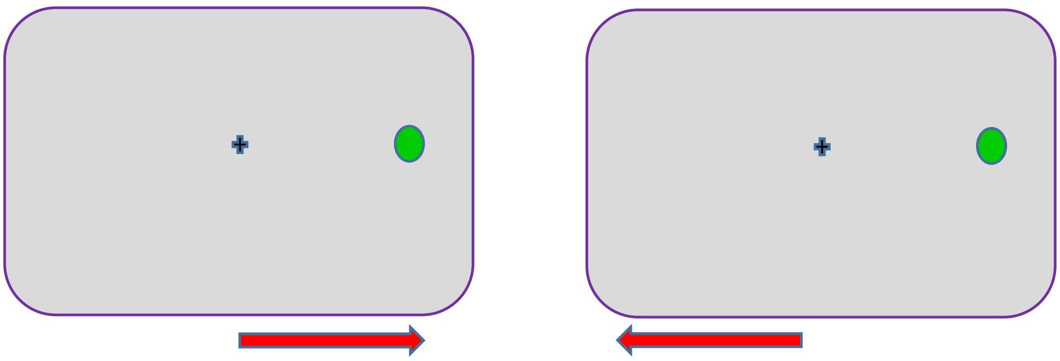


Figure 1: Prosaccade task (diagram on the left) and antisaccade task (diagram on the right)

Dual task (high depletion condition)

Adopting a dual-task paradigm, the self-control versions of each of the tasks (attention control video, Stroop and saccade tasks) were completed simultaneously with a mental arithmetic task that required working memory; the serial 15s counting task in which participants had to continually count upwards in 15s starting from 0.

Intrinsic Motivation Inventory (McAuley, Duncan, , & Tammen, 1989)

Self-reported levels of intrinsic motivation were measured by collating responses (Li et al., 2004) from the intrinsic motivation inventory (IMI), which contained 36 statements. On a 7-point-Likert scale, responses were made ranging from 'not at all true' to 'very true' to statements such as 'I enjoyed doing this activity very much', 'This activity was fun to do', 'I did this activity because I wanted to' and 'I would be willing to do this again because it has some value to me'.

Self-control scale (Tangney, Baumeister & Boone, 2004)

A 36 item self-control questionnaire was administered in which participants rated statements on a 5-point-Likert scale e.g. 'I have a hard time breaking bad habits', 'I engage in healthy practices'. Responses ranged from 1 = '*not at all like me'* to 5 = '*very much like me*'. For each participant, all responses were collated and averaged to provide an overall score.

Procedure

Participants attended one testing session, which lasted approximately 25 minutes. At the start of the session participants gave written informed consent. The first task was then completed, either a basic cognitive (control) task, a self-control task or a dual task (the self-control task paired with the counting task). Participants then scored four aspects of their performance (tiredness, effort exerted, and both how pleasant and frustrating they found the task) on a 7-point Likert scale (based on the questionnaire used by DeWall et al., 2011). The second task was then administered, which required self-control (see table 1 for the breakdown of tasks per study) and was either a similar or dissimilar task to the first. Participants subsequently completed two questionnaires – a self-control scale (Tangney, et al., 2004) and the intrinsic motivation inventory (Ryan, 1982) – before being debriefed and thanked for their participation.

Table 1.
A breakdown of the tasks completed in each study

Study number	Initial task	Second task
1	Limited time Stroop*	Antisaccade
2	Unlimited time Stroop	Anstisaccade
3	Limited time Stroop*	Unlimited time Stroop
4	Saccade	Unlimited time Stroop
5	Saccade	Antisaccade
6	Attention control video	Antisaccade
7	Attention control video	Unlimited time Stroop

Note: Studies 3 and 5 administered two identical sequential tasks.

* Task duration = 4 minutes 30 seconds

Statistical analyses

The data for each study was analysed using R (R Core Team, 2015). The package lme4 (Bates, Maechler, Bolker, & Walker, 2014) was used to conduct a linear mixed effects analysis of the relationship between performance (measured in terms of response time and accuracy) in the second task that required self-control and level of effort exerted in the initial task. We also examined the potential moderating effects of both motivation and trait self-control on task performance.

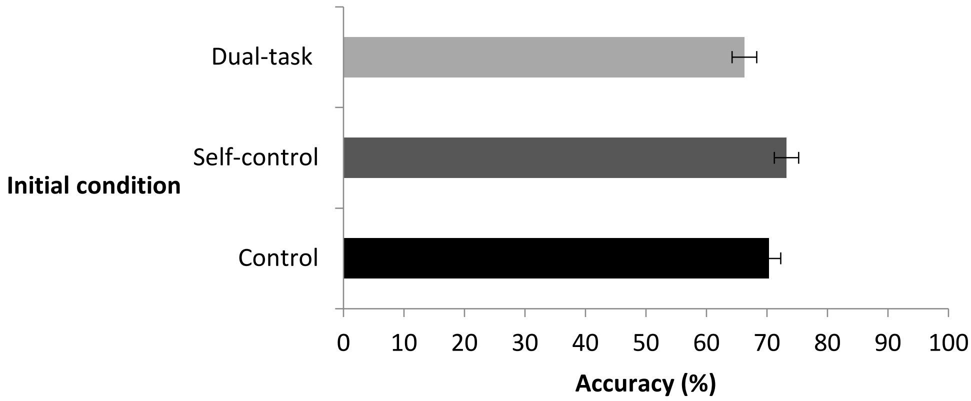
Results

Study one: The effect of completing one initial task on performance in a subsequent dissimilar task

Latency (reaction time)

Conducting a linear mixed effects analysis we added initial condition as a fixed effect and participants as a random effect. To the model we then added motivation and/or self-control as covariates and ran these separate models (with and without interaction terms). We made comparisons between each of the models by obtaining p-values from likelihood ratio tests. None of the model comparisons were significant ($p > .05$) illustrating that none of the models were a better fit for the data other than the null (intercept) model, which included participants as a random effect. Neither initial task completed, motivation nor self-control significantly predicted antisaccade response speed.

Erroneous compared to correct antisaccade responses: Firstly, fitting a model with initial condition as a fixed effect and participants as a random effect showed initial condition to not be a significant predictor of the rate of erroneous responses in the antisaccade task ($p = .84$). Adding self-control as a covariate (as well as interaction term) to the model found no significant terms in the model ($p > .05$); self-control was not a significant predictor of antisaccade error rate. We then fitted a model with motivation as a covariate (as well as an interaction term) and initial condition as a fixed effect. Motivation alone was a significant predictor of accuracy in the antisaccade task; those high in motivation irrespective of initial task made more erroneous antisaccade responses than those low in motivation ($\beta = 1.65$, $SE = .66$, $Z = 2.50$, $p = .01251$). Further, more errors were produced by those completing the initial dual task ($\beta = 15.80$, $SE = 4.89$, $Z = 3.23$, $p = .00123$) than those that completed the initial control task (see figure 2). There was a significant motivation x initial condition interaction, for the depletion (β = - 2.65, SE = 1.01, Z = -2.63, p = .00855) and high depletion/dual task (β = - 3.57, SE = 1.13, Z = -3.17, p = .00151) conditions (see figure 3). Examining these interactions further, for those completing the initial dual task, less erroneous responses were made by those high than low in motivation (β = - 2.08, SE = 1.07, Z = -1.94, p = .0524). Failing to reach significance, those high in motivation performed less antisaccade errors than



those low in motivation after completion of the initial self-control task (β = - 1.00, SE = .64, Z = -1.55, p = .120). After completion of the basic congruent Stroop task, more erroneous responses were made by those reported higher than lower in motivation (β = 1.65, SE = .67, Z = 2.46, p = .01396).

Figure 2: Percentage accuracy as a function of the initial task completed (study 1).

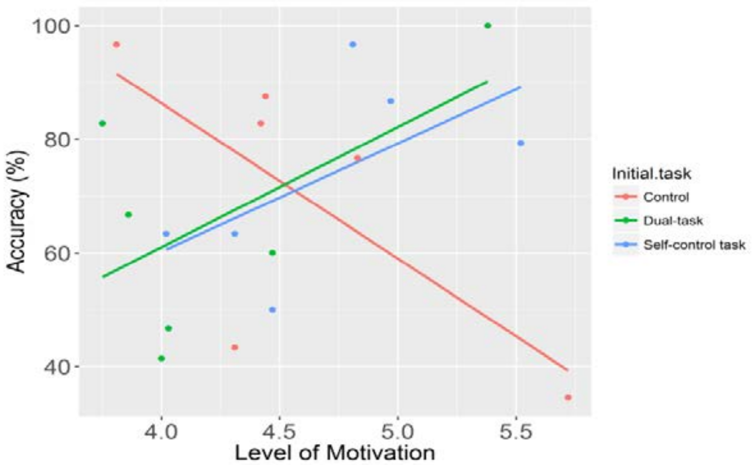


Figure 3: Accuracy as a function of level of motivation based on the initial task completed (study 1).

Study Two: The effect of completing one initial task on performance in a subsequent dissimilar task

Latency (reaction time)

Conducting a linear mixed effects analysis, we initially fitted a null model with participant as a random effect and then added initial task as a fixed effect. To build the model we then added either motivation or self-control as covariates and ran these separate models (with and without interaction terms). We made comparisons between each of the models using the p-values from likelihood ratio tests. None of the model comparisons were significant ($p > .05$) illustrating none of the models were a significantly better fit for the data and thus none of the added factors were significant predictors of response speed in the antisaccade task.

Erroneous compared to correct antisaccades

A model fitted with initial condition as a fixed effect and participants as a random effect revealed no significant effects ($p > .05$). Building the model and adding motivation as a covariate then self-control as a covariate revealed no significant main or interaction effects ($p > .05$).

Study Three: The effect of completing one initial task on performance in a subsequent identical task

Reaction time

We conducted a linear mixed effects analysis to examine the relationship between initial task completed and response speed in a subsequent incongruent Stroop task. We added initial condition as a fixed effect and participants as a random effect. To this model we then added either motivation or self-control as covariates and ran separate models (with and without interaction terms). We made comparisons between each of the models by obtaining p-values from likelihood ratio tests. None of these comparisons were significant ($p > .05$) illustrating none to be a significantly better fit than the null model for reaction time in the task.

Performance accuracy

Initially fitting a model with initial condition as a fixed effect and participants as a random effect revealed the initial task completed to significantly predict how accurate one performed in the second Stroop task. Specifically, more erroneous responses were committed in the Stroop task following the completion of the initial dual task compared to basic/control task [$\beta = 1.03$, $SE = .35$, $Z = 2.96$, $p = .00311$] (see figure 4 below). Examining the group of participants that initially completed the self-control version of the Stroop task revealed a trend for more errors to be produced by this group relative to those that completed the basic/control Stroop task ($\beta = .58$, $SE = .36$, $Z = 1.59$, $p = .11129$). Neither motivation nor trait self-control (and their interaction terms) were significant predictors of the level of accuracy performed in the Stroop task [$p > .05$].

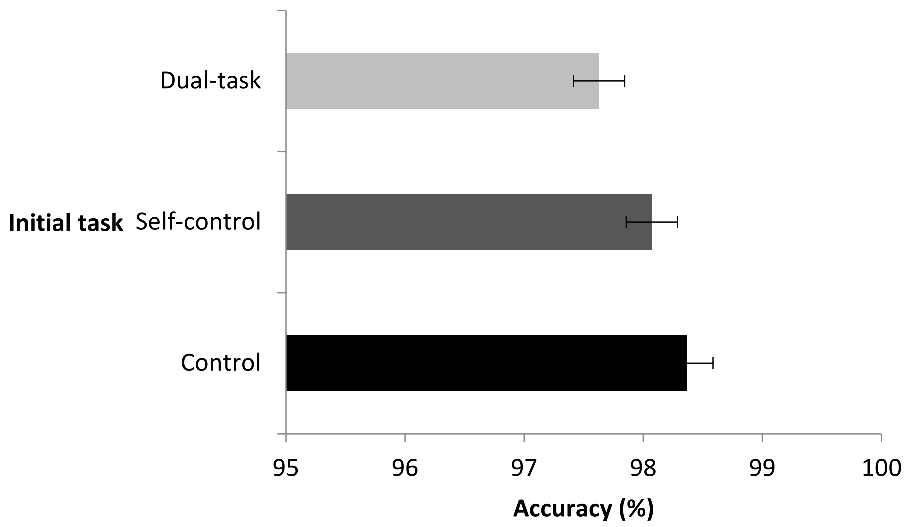


Figure 4: Percentage accuracy as a function of the initial task completed (study 3).

Study Four: The effect of completing one initial task on performance in a subsequent dissimilar task

Reaction time (RT)

Speed of Stroop response was analysed using linear mixed effects modelling. We ran through a series of models, initially adding participant as a random effect (null model) and then subsequently building the model, including initial task as a fixed effect and adding both motivation and self-control as covariates. Using the likelihood ratio tests to obtain p-values we compared the models. A significant model comparison was observed between the null model and a model fitted with initial condition as a fixed effect and motivation as a covariate (with interaction term) [$\chi 2$ (5) = 12.57, p = .002776]. No other model comparisons were significant (p > .05). Further examination of this model revealed that overall those high in motivation were faster to perform the subsequent incongruent (self-control) Stroop task than those low in motivation (β = -471.00, SE = 200.00, t = -2.36) (see figure 5).

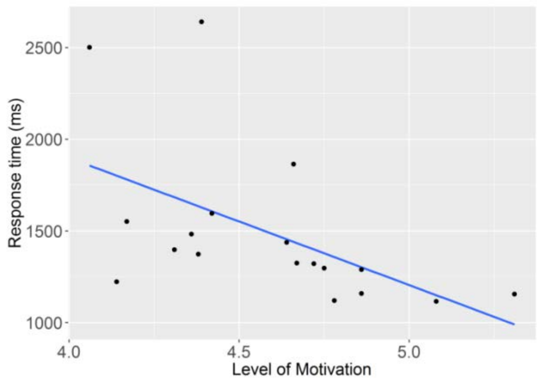


Figure 5: Stroop response time as a function of level of motivation (study 4).

Further, responses times were slower for those that completed the initial dual task compared to those that completed the initial control task (β = 5091.00, SE = 2309.00, t = 2.20). Additionally it was observed that motivation influenced response speed for those participants that completed the dual task (β = - 1067.00, SE = 491.00, t = -2.17); those high in motivation made faster responses than those low in motivation (see figure 6). Furthermore, adding self-control to the model as a covariate did not significantly predict Stroop reaction times.

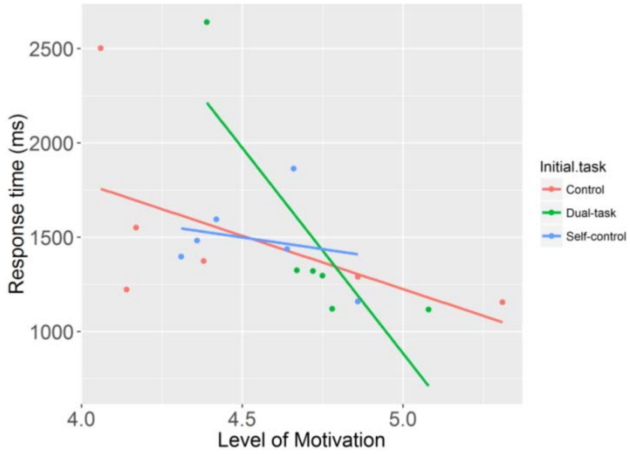


Figure 6: Stroop response time as a function of level of motivation based on the initial task completed (study 4).

Performance accuracy

Firstly fitting the model with initial task as a fixed effect and participant as a random effect revealed initial task to not significantly predict rate of accuracy. A non-significant trend suggested that those completing the initial self-control relative to control task subsequently produced more erroneous responses (β = .99, SE = .90, Z = 1.11, p = .268). There was no difference in performance accuracy between the control and dual task groups (β = -.21, SE = .91, Z = -.23, p = .820). Including individual differences in self-control as a covariate to the model produced no significant effects or interactions (p > .05). Adding motivation as a covariate produced no significant effects (β= - 2.44, SE = 1.71, Z = -1.42,p = .154). Fitting a model with participant as a random effect and motivation as a covariate revealed motivation to be a significant predictor of Stroop accuracy, irrespective of initial task completed β = -2.17, SE = 0.00, Z = -.17, p = .000); the more motivated one was regardless, the higher the rate of accuracy in the Stroop task (see figure 7).

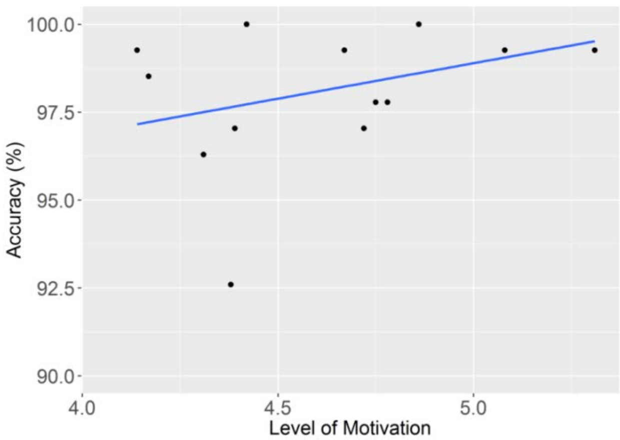


Figure 7: Percentage accuracy based on level of motivation (study 4).

Study Five: The effect of completing one initial task on performance in a subsequent identical task

Reaction time

We conducted a linear mixed effects analysis to examine the relationship between the initial task completed and antisaccade response speed. We added initial task as a fixed effect and participants as a random effect. To this model we then added either motivation or self-control as covariates and ran these separate models (with and without the interaction terms). We made comparisons between each of the models by obtaining p-values from likelihood ratio tests. None of these comparisons were significant ($p > .05$) illustrating none to be a good fit for the data when compared to the null model (fitted with participant as a random effect).

Erroneous compared to correct antisacacde responses

Firstly adding initial condition as a fixed effect and participants as a random effect revealed a higher number of errors were committed following the completion of the initial antisaccade (self-control) (β= 1.24, SE = .70, Z = 1.79, p = .07) and dual tasks (β= 1.19, SE =

.70, Z = 1.71, p = .09) compared to prosaccade (control) task, with both approaching significance (see figure 8). Adding motivation (including the interaction term) as a covariate revealed a significant motivation by initial task interaction [(β= 3.03, SE = 1.41, Z = 2.15, p = .03] (see figure 9); more errors were committed by those low in motivation following self-control exertion in the antisacacde task compared to those completing the prosaccade task. This was not extended to after the dual task was completed. Further, this model showed that those completing the initial antisaccade (self-control) task (β= 12.45, SE = 6.69, Z = -1.96 p = .05) made more erroneous responses than those that completed the prosaccade (control) task. This was not extended to the dual task group. Adding self-control as a covariate to the model produced no significant effects or interactions [p > .05].

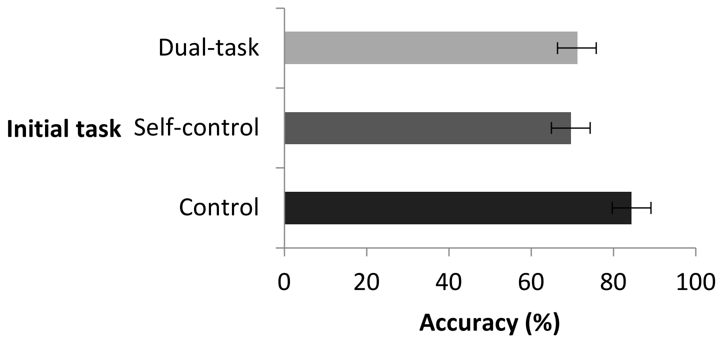


Figure 8: Percentage accuracy as a function of the initial task completed (study 5).

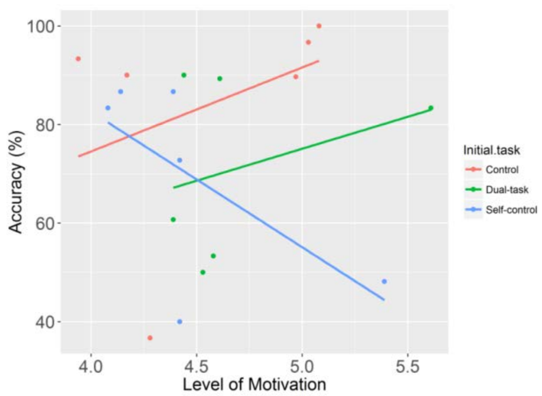


Figure 9: Percentage accuracy as a function of level of motivation based on the initial task completed (study 5).

Study Six: The effect of completing one initial task on performance in a subsequent dissimilar task

Latency/reaction time (RT)

We conducted a linear mixed effects analysis to examine the relationship between level of initial cognitive exertion and antisaccade response speed. We added initial condition as a fixed effect and participants as random effects. To this model we then added both motivation and self-control as covariates and ran through these separate models (with and without interaction terms). We made comparisons between each of the models by obtaining p-values from likelihood ratio tests. None of the model comparisons were significant ($p > .05$), suggesting that the null model (fitted with participant as a random effect) was the best fit for the data, with initial task, motivation and self-control having no significant effect on self-subsequent self-control performance.

Erroneous compared to correct antisaccade responses

A model fitted with initial condition as a fixed effect and participant as a random effect revealed initial condition to be a significant predictor of antisaccade performance accuracy. Fewer erroneous responses were committed following the dual task ($\beta = -1.77$, $SE = .97$, $Z = -1.82$, $p = .0688$) compared to those that completed the control task, with this just failing to reach significance. A similar trend emerged following the completion of the self-control task ($\beta = -1.38$, $SE = .95$, $Z = -1.45$, $p = .14510$). Adding motivation as a covariate to the model resulted in both observations being significant; completing the dual ($\beta = -1.57$, $SE = .70$, $Z = -2.24$, $p = .025258$) and self-control tasks ($\beta = -2.14$, $SE = .83$, $Z = -2.56$, $p = .010213$) led to the production of fewer errors in the antisaccade task (see figure 10). Motivation also emerged to be an approaching significant predictor of error rate; overall those high in motivation made more erroneous responses ($\beta = 1.35$, $SE = .73$, $Z = 1.84$, $p =$

.064824). Further, there was a significant initial condition x motivation interaction for those that completed the initial self-control task (β = -3.97, SE = 1.17, Z = -3.40, p = .000671) (see figure 11); those high in motivation produced significantly fewer erroneous responses than those low in motivation. This was not observed following completion of the dual task.

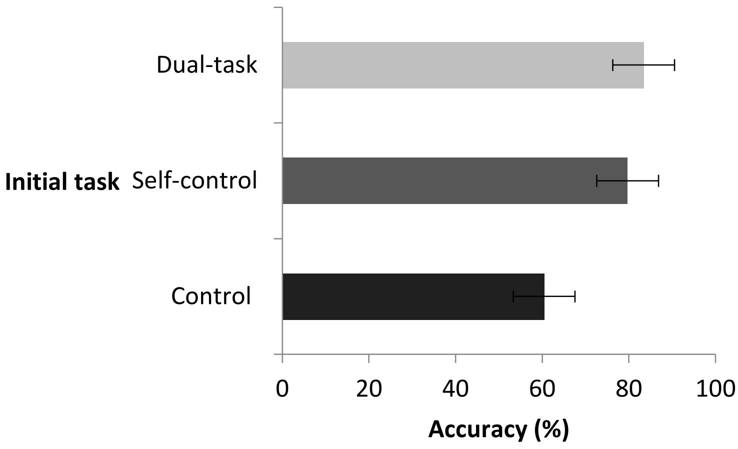


Figure 10: Percentage accuracy as a function of the initial task completed (study 6).

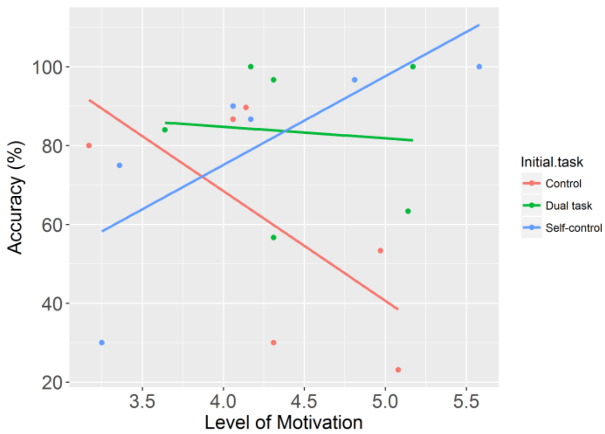


Figure 11: Percentage accuracy as a function of level of motivation based on the initial task completed (study 6).

A model fitted with initial condition as a fixed effect and trait self-control added as a covariate revealed every term in the model to be significant. Those that completed the initial self-control task (β = -6.38, SE = .84, Z = -7.62, p = .000) and dual task (β = -4.81, SE = .86, Z = -5.62, p = .000) made less erroneous responses than those that completed the initial control task. Trait self-control was a significant predictor of accuracy regardless of the initial task completed; those high than low in trait self-control produced fewer errors (β = -.09, SE = .00, Z = -52.48, p = .000). Further for those completing the initial self-control task, those high than low in trait self-control made more erroneous responses (β = .04, SE = .00, Z = 20.13, p = .000). This was also observed for those that completed the dual task (β = .02, SE = .00, Z = 10.70, p = .000); those high than low in trait levels of self-control produced more errors.

Study Seven: The effect of completing one initial task on performance in a subsequent dissimilar task

Response speed

We conducted a linear mixed effects analysis to examine the relationship between level of initial cognitive exertion and response speed in the Stroop task. We added initial condition as a fixed effect and participants as a random effect. To this model we then added either motivation or self-control as covariates and ran these separate models (with and without interaction terms). We made comparisons between each of the models by obtaining p-values from likelihood ratio tests, which revealed a significant comparison between the null model (with participant as a random effect) and a model which added initial condition as a fixed effect and self-control as a covariate ($\chi2$ (5)= 11.91, p = 0.03605). Those that completed the initial dual task (β = 2786.19, SE = 1146.58, t = 2.43) were slower to perform the Stroop task than those that completed the control version of the task (see figure 12). Self-control was a significant predictor of response speed regardless of the initial task completed; those high than low in trait self-control made slower responses (β = 26.35, SE = 9.25, t = 2.85). There was an interaction between initial condition and self-control (β -23.08, SE = 9.94, t = -2.32). Further exploration showed that for those completing the initial dual task, those high in trait self-control made slower responses than those low in trait self-control (β = 3.27, SE = 1.64, t = 2.00). No other model comparisons were significant (p > .05).

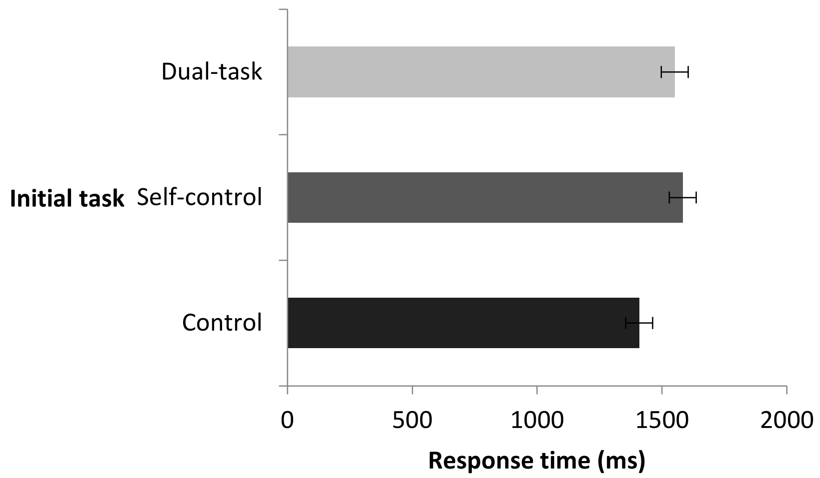


Figure 12: Stroop response time based on the initial task completed (study 7).

Performance accuracy

Initially fitting a model with initial condition as a fixed effect and participant as random effects showed initial condition to be a significant predictor of performance accuracy in the Stroop task, particularly when comparing the self-control to the control group; significantly more errors were committed after completing the self-control than control task (β = 1.21, SE = .48, Z = 2.51, p = .0122). This was also demonstrated following the completion of the dual task (high depletion), with this failing to reach significance (β = .82, SE = .49, Z = 1.66, p = .0976) (see figure 13). We then added motivation as a covariate to the model. Motivation however did not significantly predict performance accuracy in the Stroop task (β = -1.29, SE = 0.99, Z = - 1.29, p = .195). Further, adding self-control as a covariate to the model showed no significant initial condition x self-control interaction (p > .05).

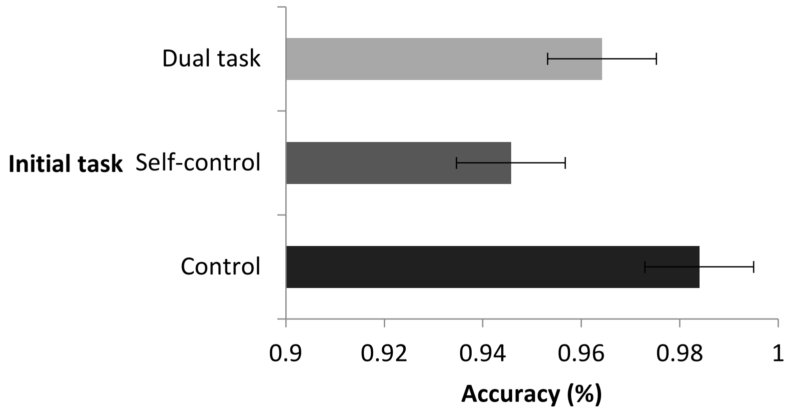


Figure 13: Percentage accuracy based on the initial task completed (study 7).

Summary of the main findings of each study:

Study one: The main aim of this study was to explore whether the initial exertion of self-control in a Stroop task would adversely affect performance in a subsequent different task; the antisaccade task. Following the completion of the initial self-control task or dual task relative to control task, more erroneous responses were made in the subsequent antisaccade task. Motivation moderated this in both groups, though stronger after completion of the dual task; less erroneous responses were made by those high in motivation.

Study two: This study had the same aim as study one but we also wanted to explore whether having no time restriction for initial task completion would influence whether a temporary deficiency in subsequent self-control performance would be observed. Findings reported no significant observations. Implementing a time duration for initial task completion resulted in findings which challenge the resource depletion theory (Baumeister et al., 1998); no temporary impairment in self-control performance was observed in the antisaccade task.

Study three: The aim of this study was to explore whether a temporary deficiency in self-control performance following previous exertion could be extended to the sequential completion of two identical tasks. The Stroop task was employed as this had been frequently used in the literature (Hagger et al., 2010). Findings revealed that more erroneous responses were made in the second Stroop task following dual task relative to control task completion. Performing a more demanding initial task led to weakened subsequent performance, supporting the resource depletion theory/strength model of self-control (Baumeister et al., 2007). A trend showed this response pattern extended to the completion of the initial self-control task. No effects of motivation or self-control were observed.

Study four: We had previously employed the antisaccade task as the second dependent measure of self-control (see Kelly et al., 2015). This study instead incorporated it as the initial task designed to deplete self-control resources and aimed to explore whether it had an adverse effect on subsequent Stroop performance. An examination of response speed showed that after completion of the initial antisaccade (self-control) task, Stroop trials were performed at a slower rate than after completion of the initial control task. However high motivation counteracted this slowing; those high in motivation, performed the trials faster. Additionally overall irrespective of initial task completed, those high in motivation made faster responses.

Furthermore a trend tentatively suggested that more errors were produced in Stroop task following completing of the initial self-control relative to control task. Participants that initially engaged in the control task and more demanding dual task produced a similar rate of errors. Motivation was observed to be a significant predictor of error rate but overall, regardless of the initial task completed, fewer errors were committed by those high than low in motivation.

Study five: Similarly to study three, the aim of this study was to explore whether a temporary deficiency in self-control performance following previous exertion could be extended to the sequential completion of two identical saccadic tasks. Findings showed that more errors were committed in the second (antisaccade) task following completion of both the dual task and antisaccade task (self-control) compared to prosaccade (control) task. This supported the results pattern of study three with the administration of two identical Stroop tasks and the expected response trajectory of the resource depletion theory (Baumeister et al., 2007): initial cognitive exertion led to a weakened performance in a second task. There was also a motivation x initial condition interaction specifically for those that initially completed the self-control task; those low than high in motivation produced more erroneous responses in the antisaccade task.

Study six: This was designed similarly to study one with the administration of dissimilar tasks but we paired the antisaccade task with another frequently used measure of self-control; the attention video task (Hagger et al., 2010). The main aim of this study was thus to explore whether initial exertion of self-control in an attention video task would adversely affect performance in a subsequent different task; the antisaccade task. Against expectations of the resource depletion theory, initially completing either the dual task or self-control task led to the production of less antisaccade errors compared to those that completed the control version of the video task. Overall trait self-control predicted performance irrespective of initial task completed; those high in trait self-control made more erroneous responses. Further, after initially completing the self-control task, those high in trait self-control made more errors

Study seven: The main aim of this study was to explore whether the initial exertion of self-control in an attention video task would adversely affect performance in a subsequent different task; the Stroop task. This task pairing was chosen deliberately as it is a combination that previous investigations (e.g. Gailliot et al., 2007) had used and therefore we wanted to observe whether we could replicate prior findings. Reflecting the response trajectory of the resource depletion theory (Baumeister et al., 2007), initially completing the attention control task in the self-control or dual task conditions led to one performing the subsequent Stroop task at both a slower rate and more erroneously. Overall if one was high in trait self-control, slower Stroop responses were made, with this being particularly prominent in those participants that engaged in the initial dual task.

Discussion

Seven studies further explored the factors that influence a temporary deterioration in self-control performance following repeated exertion across sequential tasks. The current study investigated whether completing two identical or two dissimilar sequential tasks influenced one's ability to apply self-control in a subsequent task. Supporting the resource depletion theory (Baumeister et al., 2007), it has been widely demonstrated – but recently debated (Lurquin et al., 2016; Carter et al., 2015; Hagger et al., 2015) – that completing an initial self-control task impairs performance in a subsequent self-control task. However predominantly studies employed dissimilar tasks; research lacked the administration of two identical self-control tasks (Hagger et al., 2010). The current investigation also examined whether increasing the cognitive load of the first task with a dual task - a self-control task paired with a working memory task - would produce greater self-control impairment in subsequent performance as posited by the resource depletion theory (Baumeister et al., 2007) or enhance performance (Dang, 2016). Further, the moderating effects of motivation on a temporary deterioration in subsequent self-control exertion were assessed. Previous research suggested self-control impairment was reflective of a lowering in intrinsic motivation to allocate resources to the successful completion of a task (Beedie & Lane, 2012).

Examining the studies (three & five), which administered two identical tasks, a temporary deterioration in self-control performance was observed following the administration of both the initial self-control and dual tasks (high cognitive load); performance subsequently waned. Thus depletion rather than facilitation occurred, supporting the resource depletion theory (Baumeister et al., 2007). Additionally we extended depletion effects to the sequential completion of identical tasks. This challenges the conflict monitoring account (Botvinick et al., 2001) and research evidence (Dang et al., 2014) that posits diminished task performance reflects the challenge of attending to a different task (Dang et al., 2014, Dewitte et al., 2009). For example, Wenzel, Connor and Kubiak (2013) observed that following Stroop task completion, only participants that performed a different task (resisted eating sweets) displayed a weakened self-control performance and not those that engaged in a second similar Stroop task.

Additionally study five observed motivation to have an enhancing effect on self-control performance following an initial self-control task; those high in motivation performed with greater accuracy. This was not extended to dual task completion. One could speculate that during the sequential administration of two identical tasks motivation was restorative under milder levels of depletion – for example after completing an initial self-control task - and not after greater effort is exerted following the dual task. This fits consistently with evidence from research with dissimilar tasks. Vohs, Baumeister, and Schmeichel (2012) found high motivation had no ameliorating effects on depletion after completing two initial tasks. Further, Graham, Bray and Ginis, (2014) revealed that following a third task, those higher in motivation displayed a weakened performance as increased drive (high motivation) led to the injection of more effort into the two initial tasks, providing a temporary impairment in performance in subsequent tasks.

The studies that administered two dissimilar sequential tasks produced mixed findings. Supporting the resource depletion theory (Baumeister et al., 2007), study one (Stroop task followed by antisaccade task) showed that completing the initial self-control and dual tasks led to a temporary deterioration in performance in the second task. Motivation also moderated this effect for both groups; those high in motivation performed better. This reflected the findings with identical task administration but motivation in this case also moderated performance for the dual task group, which was not observed when two identical tasks were completed. This challenges Vohs et al's (2012) findings, which observed motivation to have no enhancing effects on performance following the expenditure of more cognitive effort; completion of two initial tasks.

Findings from study four however were less clear (saccade and Stroop tasks); deterioration in subsequent performance was only observed after completing the initial self-control task and not dual task. This supports previous research which showed that performance can be enhanced if one completes two initial tasks, producing a facilitation effect (Xiao, Dang, Mao & Liljedahl 2014). Completing one initial task however produced the typical or expected pattern outlined by the resource depletion theory: a weakened performance in the second task (Carter & McCullough, 2013).

These observations were not however extended to study two, which administered the same two tasks as study one; Stroop and antisaccade tasks. Unlike study one however; study two did not impose a time limit for task completion. This is incongruent with prior studies which typically enforce a set time length for completion; thus ensuring task duration was the same, irrespective of condition (Hagger et al., 2010). Consequently, variation might have existed across participants in terms of initial self-control expenditure, which could account for these disparate findings.

Although the Stroop task has been regularly employed in studies as the initial depleting task as well as subsequent dependent measure of self-control (Hagger et al., 2010), its' implementation has been criticised. The existence of an 'ego depletion' effect in sequential self-control task designs has recently been reported to be weaker following Stroop task administration (Carter et al., 2015). This might account for the lack of consistency in the current investigation across the studies involving the Stroop task.

Further, studies six and seven added to the debate over the conditions that might foster ego depletion. Study seven provided support for the resource depletion theory (Baumeister et al., 2007) as a weakened subsequent performance was displayed by participants that completed either the dual task or self-control tasks relative to control task. However findings from study six challenged this as performing the initial self-control and dual tasks led to better subsequent task performance, supporting a facilitation effect.

Additionally, both studies six and seven observed trait self-control to have a moderating effect on self-control performance; those high in self-control displayed a weakened subsequent self-control performance, following prior exertion. This challenges prior findings; it was expected that those high in trait self-control would show an enhanced self-control performance as one should be less vulnerable to self-control depletion (Muraven, Collins, Shiffman & Paty, 2005; Gailliot et al., 2007). However more recent research failed to replicate this (Salmon, Adriaanse, De Vet, Fennis & De Ridder, 2014); individuals high in trait self-control observably make more hazardous choices (Imhoff, Schmidt, & Gerstenberg, 2013). The current investigation thus further adds to the mixed and inconclusive findings on the moderating effects of trait self-control on self-control ability.

Some findings observed impaired subsequent task performance following dual task completion, which involved both self-control and working memory. This could suggest that both of these executive functions have overlapping processes (Anguera et al., 2012). Indeed previous studies employed working memory tasks (e.g. Schmeichel (2007) within a sequential self-control depletion paradigm and observed negative transfer between the two executive control tasks. It would be unlikely that performing one task influenced another if the tasks drew on dissimilar resources/processes (Anguera et al., 2012). The current study supplemented this by exploring whether a temporary impairment in performance in the second of two sequential tasks was specific to the completion of self-control tasks or whether the effect generalised to other forms of cognition that required executive control, such as working memory.

It is worth noting that we only observed performance differences in the majority of studies for performance accuracy and only two of the studies (six and seven) observed differences for response time. Previous research however indicates that the effects of prior self-control exertion on subsequent performance can be measured with either performance parameter; response time and/or accuracy (Carter et al., 2015).

The small sample size of each study may limit the generalisation of findings. Previous self-control studies have been criticised for employing small samples, suggesting that the ego depletion effect might be limited to smaller sized samples and therefore advising future research to conduct larger studies with more power (Carter & McCullough, 2014). Despite this, the series of studies in this investigation provided an insight into a number of debated topics within the ego depletion literature; identical task administration, facilitation versus depletion, and generalisation to another executive function (working memory). The findings suggest the antisaccade task can be implemented successfully into a self-control depletion paradigm; further studies expanding on the current findings, with larger sample sizes are needed.

In conclusion, the results extend depletion effects to the administration of two identical tasks, supporting the resource depletion theory; performing an initial dual task (high depletion) or self-control task compared to basic control task led to a temporary deterioration in subsequent self-control performance. Motivation was observed to counteract performance following the completion of an initial self-control task in isolation. However for the completion of dissimilar tasks, mixed findings were observed, which adds to the debate about the tenability of the ego depletion effect i.e. that a temporary impairment in self-control performance occurs in the second of two sequential self-control tasks (Hagger et al., 2015;

Dang, 2016). The robustness of prior findings has been questioned (Carter et al., 2015) with more recent research failing to replicate previous ego depletion effects (Xiao et al., 2014; Kelly et al., 2015; Hagger et al., 2015). The series of studies in the current investigation provide further insight into sequential self-control performance and the conditions that might foster a temporary deterioration in self-control performance as well as potential moderating effects of intrinsic motivation on sequential self-control task performance.

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Paper three: Sequential task performance: the modulating effects of motivation, task adaptation and glucose regulation on continued cognitive exertion.

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Abstract

Research suggests that exerting self-control relies on the availability of a limited resource and completing consecutive self-control tasks lowers this resource resulting in weakened performance. Glucose is argued to be the resource, with glucose administration ameliorating this effect. Some research suggests the effect is not specific to self-control but can be applied more generally to cognitive tasks, such as working memory, which also requires executive control. The current study examined the effect of glucose administration on sequential executive control task performance and assessed whether differences in glucose regulation influenced task performance. Research suggests that motivation is a powerful predictor of self-control and thus was explored as a potential modulator of performance. In a double-blind design, 58 young healthy adults received a 40g glucose or a placebo drink after completing two initial tasks - the reverse digit span task and either an incongruent or congruent (control) Stroop task – and before administration of the prosaccade and antisaccade tasks. The results of the study showed that glucose consumption did not influence antisaccade performance and performing the initial tasks did not alter peripheral blood glucose levels. The number of initial tasks completed predicted antisaccade performance; those completing the reverse digit span task paired with basic congruent Stroop task (one cognitively effortful task) committed more errors. Those completing three consecutively effortful tasks showed enhanced antisaccade performance, supporting adaptation. Motivation predicted antisaccade performance; those high than low in motivation performed the task more accurately, which was stronger after completion of one initially cognitively effortful task paired with basic task. Individual differences in glucose regulation predicted self-control performance; those with poorer glucose regulation displayed a weakened performance in both the incongruent Stroop and antisaccade tasks but were no more vulnerable to depletion. Overall, the findings extended depletion effects to more general complex cognition, and showed that the number of initial tasks completed, motivation level and glucose regulation are important modulators of performance.

Key words: self-control, cognitively effortful task, glucose, motivation, adaptation, glucose regulation

Sequential task performance: the modulating effects of motivation, task adaptation and glucose regulation on continued cognitive exertion.

Self-control involves exercising control over one's behaviour such as the inhibition of automatic/impulsive actions (Baumeister, 2012; Gailliot et al., 2007). For example, aggression control, suppressing emotions and dieting all require self-control. It is regularly exercised each day (for an average of approximately four hours within a 24-hour period) and plays an important role in social order; ensuring individuals conform to societal standards of behaviour (Hoffman et al., 2012).

Despite its importance, failures in self-control are common. An accumulation of research shows that repeated application of self-control can be difficult. For example, performing two tasks that require self-control in close succession has widely been shown (in over approximately 80 studies) to produce a temporary performance decline in the second task (Hagger et al., 2010). Baumeister, Vohs and Tice (2007) proposed the resource depletion theory/strength model of self-control, which posits that one's ability to exercise self-control is contingent on the availability of a limited resource. Therefore, exerting self-control reduces the amount of available resources left for continued exertion, resulting in a temporary impairment in successive efforts.

Research suggested that this resource is glucose. For example, Gailliot et al. (2007) reported that initially exerting self-control produced a reduction in peripheral levels of blood glucose and consuming a glucose drink enhanced subsequent performance. The ameliorating effect of glucose administration on a temporary deficiency in self-control was supported in further studies (e.g. Wang & Dvorak, 2010, Denson, von Hippel, Kemp & Teo, 2010; DeWall, Baumeister, Gailliot & Maner, 2008).

However more recent findings have challenged the assertion that self-control results in a reduction of peripheral and/or central glucose levels (e.g. Kurzban, 2010; Kelly, Sünram-

Lea & Crawford, 2015; Sanders, Shirk, Burgin & Martin, 2012; Molden et al., 2012; Lange & Eggert, 2014). Specifically, using a sequential two task paradigm, studies have failed to replicate the amelioration of self-control deficit on the second task following glucose administration (for a recent review see Lange, 2015). And a recent meta-analysis reported no direct relationship between peripheral and/or central glucose availability and self-control capacity (Dang, 2016). Moreover, mouth rinsing with glucose, which does not increase peripheral and central glucose availability has been shown to have the same restorative effects on self-control performance as glucose ingestion (Hagger & Chatzisarantis, 2013; Molden et al., 2012). Although, this finding was not replicated (Lange & Eggert, 2014), it has been suggested that glucose enhances motivation levels through glucose in the mouth triggering reward centres in the brain (Chambers et al., 2009).

Indeed, level of motivation, irrespective of glucose availability has increasingly been reported to be a powerful predictor of self-control, restoring the effects of self-control depletion following prior exertion (Muraven & Slessareva, 2003; Klinger, 2013). For example, the resource allocation account (Beedie & Lane, 2012) posits that if a task is deemed to be meaningful or important one will be more motivated to divert resources to a subsequent task, ensuring successful completion. Using a sequential self-control task design we previously observed that high levels of motivation counteracted weakened performance in the second self-control task (Kelly et al., 2015). This is also consistent with the shifting priorities non-resource account that suggested that if a task is personally relevant or if there is choice over task selection this increases motivation to successfully engage in the task (Inzlicht et al., 2014; Legault & Inzlicht., 2013).

Studies examining the effects of glucose on various aspects of cognitive performance, have demonstrated that effects are significantly moderated by individual differences in glucose regulation, even in young healthy adults. For example, those with better glucose regulation (those with the smallest blood glucose rise following glucose ingestion) performed better on tests of memory (Awad, Gagnon, Desrochers, Tsiakas, & Messier, 2002; Messier, Desrochers, & Gagnon, 1999; Sünram-Lea, Owen, Finnegan, & Hu, 2011; Owen, Scholey, Finnegan, & Sünram-Lea, 2013; Owens & Benton, 1994: Donohoe & Benton, 1999), vigilance (Benton & Owens, 1994: Donohoe & Benton, 1999), planning (Donohoe and Benton, 1999) and dichotic listening (Parker & Benton, 1995) compared to those with poorer glucose regulation. Additionally, glucose administration preferentially improved performance in those with poorer glucose regulation and the effects were less likely to be observed in good glucose regulators across old and young populations (Messier 2004).

Applying this to self-control, a positive correlation was reported between self-reported levels of aggression (using the Aggression Questionnaire; Buss and Perry, 1992) and diabetic status (Dewall, Deckman, Gailliot & Bushman, 2011). However, diabetic status was assessed using a diabetic symptom checklist and not through assessment of glycaemic response to a glucose load. The gold standard method to assess glucose regulation is the Oral Glucose Tolerance Test (OGTT), where glycaemic response to a 75g glucose load is assessed over a two hour period. Using this method, glucose regulation has been shown to predict performance on self-control measures, namely the incongruent Stroop task (Gluck, Ziker, Schwegler, Therle, Votruba & Krakoff, 2013) and the ability to inhibit particular words and recall certain items (Elliot, 2010); those with good glucose control performed better.

Eriksson et al. (2012) observed that males with poorer than better glucose regulation were more impulsive (a sign of poorer self-control). Furthermore, Zahn, Tug, Wenzel, Simon, and Kubiak (2016) found a significant relationship between insulin resistance – where glucose cannot be efficiently absorbed from the blood and thus negatively impacts on effective glucose metabolism - and self-control; those with high insulin resistance reported lower levels of self-control. However, this did not extend to the objective assessment of sequential self-control performance; no significant relationship between insulin resistance and self-control/inhibitory performance was observed. Consequently, differences in glucose control might explain the response variability observed in human studies.

Few studies have examined the relationship between glucose regulation and sequential self-control task performance. As the role of glucose in self-control ability has been widely explored, the current study assessed whether those with poorer glucose regulation (assessed using an OGTT with 20 participants) produced a weakened self-control performance irrespective of initial exertion or whether vulnerability to a greater deterioration following initial cognitive exertion would occur.

Self-control or general cognitive depletion?

Evidence shows that some studies designed to assess sequential self-control performance employed tasks that tapped into additional cognitive domains such as other executive functions (EFs) like working memory (e.g. Carter & McCullough, 2013; Imhoff, Schmidt & Gerstenberg, 2014). Working memory is vulnerable to similar depletion effects (Conway & Engle, 1996; Ackerman & Kanfer, 2009; Cook, Ball & Brewer., 2014) and like self-control, is involved in the top-down processing of information which is conscious, purposeful and effortful (Diamond, 2013; Miyake, Friedman, Emerson, Witzki, Howerter, & Waher,. 2000). Schmeichel (2007) observed prior engagement in a self-control task reduced one's ability to perform a working memory task. Additionally, following the completion of an initial self-control task, participants primed to the belief that their cognitive capacity will be reduced after self-control exertion, displayed a weakened working memory performance (Clarkson, Hirt, Chapman & Jia, 2011). Further, research showed that previously remembering a 7 compared to a 2-digit number (control condition) led to one being less likely to display self-control and choose chocolate cake over a heathier food option (Shiv & Fedorikhin, 1999).

These findings support the resource depletion theory but challenge its' specificity to self-control tasks; an initial cognitively demanding working memory task impaired performance on a subsequent equally as demanding task (Cook et al., 2014). One could speculate that the tasks relied on similar resources/processes (Anguera et al., 2012), illustrating more general cognitive depletion. Tapping into this further, the current study administered a working memory task within a sequential task design.

Number of sequential tasks

Typically, previous research examining the resource depletion theory adopted a two task paradigm involving the completion of two sequential self-control tasks (Hagger et al., 2010). Limited research has explored the effect that completing two or more initial activities has on subsequent performance in a later task (Converse & DeShon, 2009). According to the resource depletion theory greater cognitive exertion – completing more tasks – results in a greater temporary deficiency in subsequent performance (Baumeister, Vohs & Tice, 2007). For example, after engaging in two initial self-control tasks a greater weakening in performance was observed on a later third task (Vohs, Baumeister & Schmeichel, 2012).

The adaptation account – based on Helson's (1964) adaptation theory – however, suggests that more cognitive exertion results in adaptation to the task demands leading to a stable or enhanced level of subsequent performance (Converse & Deshon, 2009). For example, being given time to adapt to the initial tasks counteracted any depletion effects (Dang et al., 2013). Further, Carter and McCullough (2013) and Xiao, Dang, Mao and Liljedahl (2014) both reported that completing two initial self-control tasks led to no impairment in subsequent performance in a cognitively demanding task.

Examining any motivation effects, evidence showed that high levels of motivation counteracted a temporary deficiency in subsequent self-control performance following prior exertion with two sequential tasks but not three; those high in motivation displayed a weaker performance in the last of three consecutive tasks (Graham, Bray & Ginis, 2014). One could speculate that motivation might have a restorative effect for only a limited number of sequential tasks. The current study tapped into this by administering more than two sequential tasks and measuring intrinsic motivation as a potential moderating factor.

The current study

Adopting a similar sequential task paradigm to previously (Kelly et al., 2015), we explored whether a deficiency in performance in the antisaccade task (Hallett, 1978) occurred following the completion of a working memory (reverse digit span) task paired with either an incongruent (required self-control) or congruent (basic test that requires no self-control) Stroop task. The reverse version of the working memory task is more cognitively effortful and places greater demands on working memory than the forward version (Laures-Gore & Verner, 2008). This assessed general cognitive ability; whether performing a working memory task adversely affected subsequent self-control performance. Further, we explored whether a temporary deficiency in performance would be likely following the completion of three cognitively effortful tasks or whether one would display a performance pattern congruent with the adaptation account. The current study examined the role of glucose on self-control and assessed whether motivation level irrespective of glucose significantly predicted subsequent antisaccade performance. The modulating effect of individual differences in trait self-control on sequential performance was also assessed through self-report measurements. Previous findings have been mixed. And in fact against expectations, our previous study (Kelly et al., 2015) reported those high in self-control to benefit from glucose consumption in terms of an enhanced subsequent self-control performance. Therefore further investigations were needed to explore the potential modulating effects of differences in trait self-control on self-control performance. Coupled to this, glucose regulation (using a sample subset; N = 20) was measured to observe whether individual differences in glucose regulatory control influenced self-control performance during sequential task completion.

Method

Design

The effect of consuming one of two drink solutions (40g glucose vs. placebo) on performance was examined following a double-blind 2 (initial condition: one vs. two cognitively effortful tasks) x 2 (drink condition: 40g glucose, placebo) x 2 (eye movement task: prosaccade, antisaccade) mixed-factorial design with the third factor as a repeated measure. For the OGTT, there were 5 participants in each of the conditions in the 2 (initial condition) x 2 (drink) between subjects design.

Participants

Two participants were excluded on the grounds that the saccade tasks could not be successfully completed and were removed from the analysis. This resulted in a final sample of 58 healthy young adults (22 male & 36 female) studying at Lancaster University with a mean age of 20.97 (SD = 3.32) and average BMI of 22.67 (SD = 2.81). The sample size was sufficiently powered according to Cohen's (1971) standards. Participants were screened and could not take part if they had diabetes mellitus (and/or history of the illness), any intolerance or allergic reaction to sugar or sugar/substitutes or substances that contain phenylalanine, were pregnant and/or lactating. Lancaster University Ethics Committee provided ethical approval and each participant signed a written informed consent sheet before starting the study.

Materials

Reverse digit span test (working memory task): Based on the original design by Corsi (1972), a computerised version of the nine-block task (via a Computerised Mental Performance Assessment System; COMPASS) was administered in which participants were instructed to remember sequences of blocks on a computer screen and then select the correct sequence displayed but in the reverse order. The test started with one block being highlighted, with the number of blocks to be remembered rising sequentially by one until the participant performed an incorrect sequence.

Stroop task: A computerised version of Wallace and Baumeister's (2002) Stroop task was administered in which participants had to respond to the colour of 135 colour words (blue, green, yellow, purple or red). A congruent version was completed in which the ink colour and the colour words were matched or an incongruent version, in which they were mismatched. Additionally, in the incongruent version one had to ignore this when the colour was 'Red' and state the actual word. A time limit was imposed for the presentation of each word, ensuring both versions of the tasks were matched for a duration of four minutes thirty seconds. Participants made their responses out loud as well as pressing keys on a QWERTY key board.

Following Stroop task completion, a manipulation check was administered, which tapped into four aspects of performance - pleasantness, level of effort exerted, frustration with the task and tiredness (see Denson et al., 2010) – and assessed whether the incongruent than congruent version of the Stroop task was more difficult to complete.

Saccade tasks*:* Overlap versions of both the prosaccade (eye gaze directed towards a target) and antisaccade (suppression of an automatic prosaccade and directing one's eye gaze away and in the opposite direction to the target) eye movement tasks were completed. The prosaccade was administered before the antisaccade task, as previous research observed this optimal due to possible carry-over effects across the two tasks (Roberts, Hare & Hager, 1994). Participants were asked to place their head comfortably on a chin rest located 57 cm from a 19″ computer screen, which displayed the saccade tasks. An Eyelink 1000 (SR Research: 1,000 Hz, <.5° accuracy) recorded latencies of saccades towards and away from the target. During both tasks, a fixation cross was presented in the centre of the screen. After 1,000 ms, a small green dot (.6° diameter) appeared 8° to the left or to the right of the fixation cross. Both the target and cross remained on the screen for 1,000 ms (overlap), and a 1,500-ms interval preceded the next trial. The location of the target was randomised and appeared on the left or right with equal frequency.

Drinks: 250ml 40g glucose or inert placebo (5 Saccharin sweetener tablets; Sweetex tablets) drinks, matched for taste and flavoured with unsweetened lemon juice (10ml) were randomly administered in clear cups, following a double-blind procedure. A sensory evaluation of the drinks confirmed that the glucose drinks were liked on a comparable level to the placebo drinks [$\beta = .54$, SE = .30, $t = 1.81$, $p = .08$].

Blood glucose readings: Peripheral blood glucose levels were measured using the ExacTech glucose measuring device at baseline, after the first two tasks (reverse-digit span and Stroop) and at the end of the testing session. This device is widely used by patients with diabetes mellitus and is considered a sensitive measure (Rebel, Rice & Fahy, 2012). A recent study found a significant correlation between glucose measured in the capillary (finger prick) and arteriovenous (AV) blood (Dye et al., 2010).

Self- control scale [Tangney, Baumeister & Boone, 2004]*:* The scale contained 36 items and was used to examine participant's self-reported level of trait self-control. Each item was rated using a 5-point-Likert scale (1 = '*not at all like me'* to 5 = '*very much like me*') providing an overall score.

Intrinsic Motivation Inventory (IMI) [McAuley, Duncan & Tammen, 1989]: Participants' self-reported level of intrinsic motivation was examined using a 36 item IMI. Responses were formed on a 7-point-Likert scale varying from '*not at all true*' to '*very true*'. Sentences that demanded a response comprised, 'I enjoyed doing this activity very much', 'This activity was fun to do', 'I did this activity because I wanted to' and 'I would be willing to do this again because it has some value to me'. Responses were collated to provide an indication of how motivated participants were to complete the saccade tasks (Li et al., 2004).

Oral Glucose Tolerance Test (OGTT): Glucose tolerance was assessed over a two-hour period in the morning with an OGTT; baseline blood glucose readings (0 minutes) were assessed at 09:00, followed by administration of a 75g glucose drink (flavoured with unsweetened lemon juice) and four further readings at half hourly intervals post drink-ingestion (30, 60, 90 & 120 minutes). Participants were instructed to refrain from the consumption of any food or drink (except water) for at least 12 hours prior to the study session.

Procedure

Participants fasted for two hours prior to the session. Participants firstly provided written informed consent and answered some demographic questions detailing their height, weight and age. Baseline blood glucose levels were measured (t1) and then participants completed two initial tasks; the reverse-digit span task followed by either the congruent or incongruent Stroop task. A second blood glucose reading (t2) was then taken and using a double blind procedure; the drinks were administered in clear plastic cups and consumed within five minutes. To allow for glucose absorption, participants waited 15 minutes before completing the prosaccade and antisaccade tasks. During this period, participants completed the self-control questionnaire (Tangney et al., 2004) and the eye tracking equipment for the saccade tasks were set up. After completing both eye movement tasks, a third (t3) and final blood glucose reading was measured and participants completed the intrinsic motivation inventory before being thanked and fully debriefed.

OGTT testing session*:* On a separate testing day, a subset of the sample (N = 20) took part in a testing session in which they received a two hour OGTT. Following a baseline blood glucose reading, a 75g glucose drink was administered with blood glucose being measured at subsequent half hourly intervals following drink consumption.

Statistical analysis

Saccade response times (RTs) were computed as the delay between target onset and the beginning of the first saccade, with an amplitude of greater than 2°. Responses below 80 ms or over 500 ms were considered anticipatory or late saccades, and were not included in the analysis. Performance accuracy was calculated by recording correct and erroneous saccade (directional error) responses.

Using the lme4 package in R (R Core Team, 2015), saccade RTs were analysed using linear mixed-effects modelling and performance accuracy was assessed with Generalised Linear Mixed effects Modelling (GLMM). Running through a series of separate models for the two performance parameters, we included participants as random effects - to address unexplained variation between participants (Winter, 2013) - and type of saccade task (prosaccade and antisaccade) as a fixed effect for saccade latencies only. Both initial condition (number of cognitively effortful initial tasks completed) and drink condition were added as fixed effects. Level of motivation and individual differences in self-control were added as covariates to the models to examine whether individual differences in these self-reported measures influenced saccade performance. For saccade RTs we made comparisons between the models by obtaining p-values from likelihood ratio tests.

In addition, changes in peripheral levels of blood glucose were analysed using linear mixed effects modelling. Participants were added as random effects and time (baseline, post initial tasks and post saccade task completion) and drink condition were treated as fixed effects. Including self-reported levels of motivation as a covariate within the model assessed whether motivation level significantly predicted glycaemic response.

OGTT: Results of the OGTT were analysed using linear mixed effects modelling in which a series of separate models for the two performance measures in the saccade tasks (RTs & erroneous antisaccade responses) were conducted to examine the relationship between saccade task performance and individual differences in gluco-regulatory control. To the model, participants were included as random effects and task type for saccade RTs, initial condition and drink condition were added as fixed effects. To the model we then added glucose regulatory control as a covariate and ran these separate models. For RTs we made comparisons between each of the models by obtaining p-values from likelihood ratio tests.

Separately, following a correlational analysis we used linear model analysis to also assess whether individual differences in glucose regulation significantly predicted working memory ability and Stroop performance accuracy.

Results

Stroop Performance

Manipulation check: Using linear modelling analysis we observed no significant differences between the congruent (control) and incongruent (self-control) versions of the Stroop task in self-rated levels of tiredness [$\beta = -.33$, SE = .34, $t = -.96$, $p = .34$] or task pleasantness [$\beta = .15$, SE = .28, $t = .53$, $p = .60$]. However, participants completing the incongruent Stroop task reported to exert greater effort [$\beta = -2.01$, SE = .37, $t = -5.38$, $p <$

.001] and found the task more frustrating to complete [β = - 1.83, SE = .44, t = - 4.14, $p < .001$] than those that completed the congruent (control) version.

Accuracy: Performance accuracy in the incongruent version of the Stroop task, which required self-control was significantly lower (M = 86.43, SD = 11.37) compared to the congruent (control) version (M = 99.33, SD = .88) of the task [β = - 12.91, SE = 2.08, t = 6.20, $p < .001$].

Drink condition

Glycaemic response: To the model we added time of measurement, initial condition and drink condition as fixed effects and participant as a random effect. The analyses revealed a significant effect of time; readings at t3 were significantly higher than at t1[β = 3.33, SE= .34, t = 9.69, $p < .001$]. There was a significant time x drink condition interaction [β = - 3.43, SE = .49, t = - 7.05, $p < .001$], which revealed that following glucose compared to placebo consumption blood glucose readings were significantly higher at t3 (i.e. after drink administration) compared to baseline (t1). Initial condition was not a significant predictor of blood glucose reading nor was there a significant time x initial condition interaction ($p > .05$). We evaluated the effect of motivation on blood glucose levels - as these might be affected by level of motivation due to potential differences in neuroendocrine activation - by adding motivation to the model as a covariate. This revealed a significant time x initial condition (one vs two cognitively effortful tasks) x motivation interaction (β = 0.33, SE = 0.15, t = 2.16, p = 0.03). Examining the interaction revealed that irrespective of the drink consumed; completion of the working memory task paired with congruent Stroop task (one cognitively effortful task) was associated with higher blood glucose levels at t3 and a higher level of motivation (see figure 1).

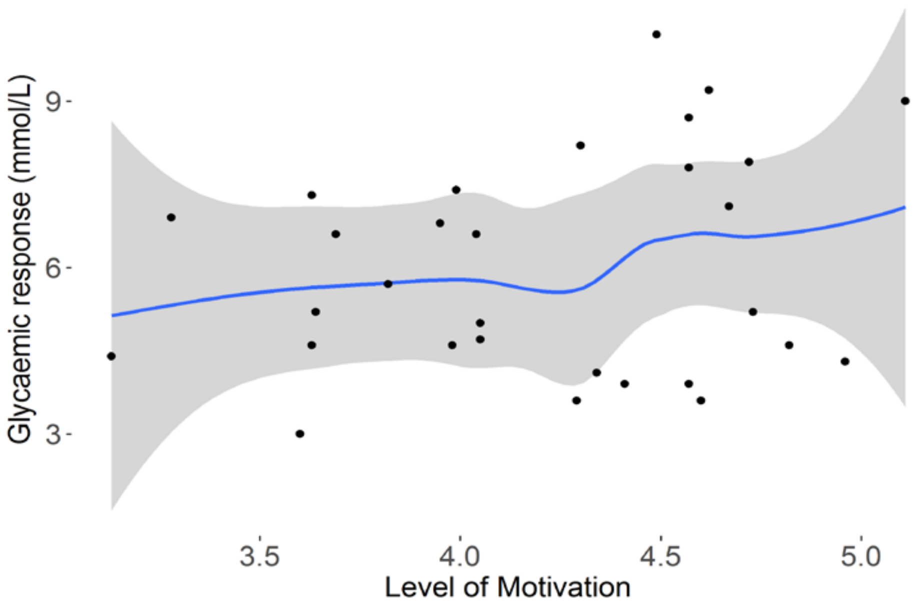

Figure 1: The association between peripheral blood glucose levels measured at time 3 and motivation level.

Glycaemic response before and after initial task completion: To evaluate whether initial task completion influenced glucose levels, we analysed peripheral blood glucose levels before and after the initial tasks were completed using linear mixed effects modelling. Adding initial condition (one vs. two cognitively effortful tasks) and time of glucose reading (t1; baseline vs. t2; post-Stroop) to the model as fixed effects and including participants as random effects, neither initial task [β = - .22, SE = .46, t = - .48, p = .64] nor time [β = - .12, SE = .21, t = - .56, p = .57] were observed to be significant predictors of glycaemic response. The initial condition x glucose reading interaction was also not significant [β = .05, SE = .29, t = .18, p = .86].

Saccade performance

Performance accuracy (rate of erroneous responses) in the antisaccade task

Accuracy of responses were analysed using GLMM. Initially, the model was fitted with participant as a random effect and number of initial cognitively effortful tasks completed (initial condition) as a fixed effect. This revealed initial condition to be a significant predictor of AS responses; significantly more errors were committed following the completion of the working memory paired with congruent (control) than incongruent (self-control) Stroop task (β = - 1.07, se = 0.39, z = - 2.77, p = .006) [see figure 2]. We then added drink condition as a fixed effect, which did not significantly influence directional error rate (β = - .26, SE = 0.51, z = - .51, p = .61), nor was there a significant initial condition x drink interaction (β = .30, SE = 0.77, z = .38, p = .70). However, adding motivation as a covariate to the model resulted in this being a significant predictor of directional error rate regardless of the initial tasks completed (see figure 3); those high in motivation produced fewer errors (β = - 0.97, SE = 0.48, z = - 1.99, p = .0471). The initial condition x motivation did not reach significance (p = .35). Further examination however revealed that motivation was a significant predictor of the rate of directional errors for those participants that engaged in the working memory task and basic congruent Stroop task only (β = - 0.99, SE = 0.51, z = - 1.97, p = .0491); higher motivation was paired with the production of less directional errors in the antisaccade task (see Figure 4). Motivation did not significantly predict performance in those participants that completed two initial cognitively effortful (working memory paired with incongruent Stroop) tasks (β = - .38, SE = 0.38, z = - .97, p = .331).

Further, a model fitted with participant as a random effect, self-reported levels of trait self-control as a covariate and initial condition as a fixed effect observed initial condition to be a significant predictor of error rate in the antisaccade task (β = - 1.10, SE = 0.39, z = - 2.84, p = .00449); less errors were committed by those completing two initially cognitively effortful tasks (working memory task paired with incongruent Stroop task). Self-control did not significantly predict performance nor was there a significant initial task x self-control interaction (both $p > .05$).

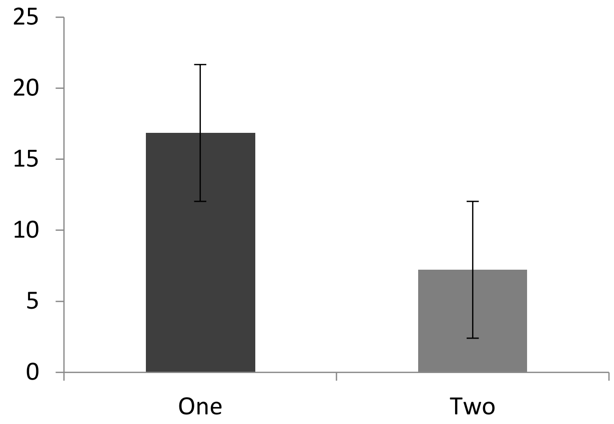

Figure 2: Antisaccade error rate as a function of initial condition

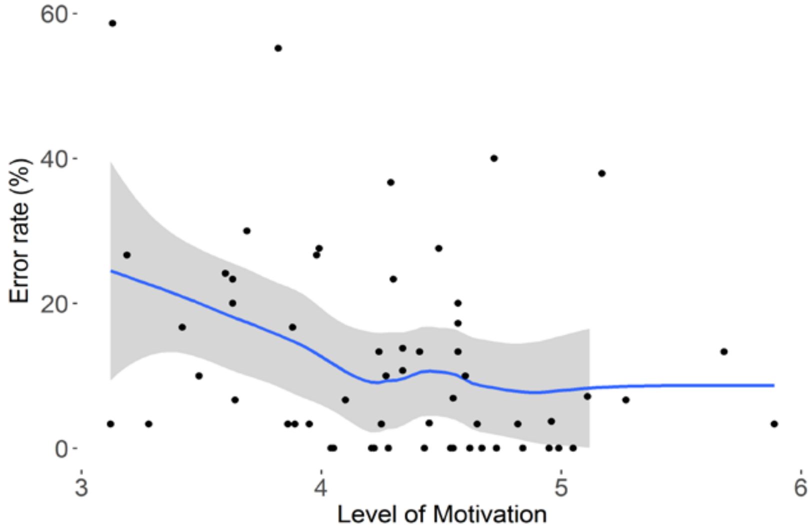

Figure 3: Antisaccade error rate as a function of motivation

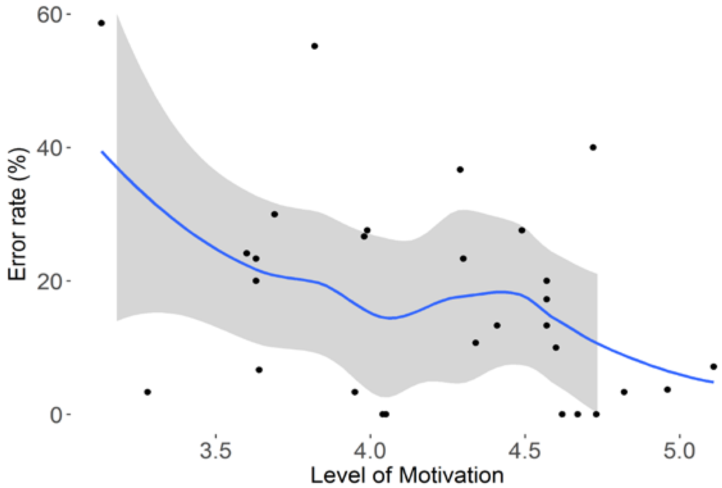

Figure 4: Antisaccade error rate as a function of motivation for participants that completed one initial cognitively effortful task.

Saccade RTs

We ran through a series of models incorporating participants as a random effect and adding step by step different fixed effects and covariates. Likelihood ratio tests then compared the different models. Adding task type as a fixed effect (model 3) improved the model fit significantly compared to the intercept model (model 1) [$\chi (1)^2 = 739.61$, $p < .001$]. This was reinforced by an examination of the BIC; model 2 (-4953.30) had a lower BIC than model 1 (-4221.80). This illustrated that task type was a significant predictor of response speed; prosaccade responses were significantly faster than antisaccade response ($\beta = -.11$, SE = .00, t = - 28.80). No other model comparisons were significant (all $p > .05$) illustrating that model 2 was a significantly better fit and explanation for the data.

Analysis of the sample subset that completed the Oral Glucose Tolerance Test (OGTT)

Saccade performance

Sacccade RTs

Initially we fitted the model with participant as a random effect and task type (prosaccade and antisaccade) as a fixed effect (model 2). Compared to the intercept model (model 1) [BIC =-1478.70] this was a significantly better fit for the data [$\chi (1)^2 = 263.51$, $p < 2.2 \times 10^{-16}$] and had a lower BIC [-1740.20]. Thus task type significantly predicted speed of responding in the saccade tasks; prosaccades were significantly faster than antiscacades ($\beta = -.11$, se = .01, t = - 17.20). Further model comparisons using the likelihood ratio test revealed a model with both initial condition and task type as fixed effects and participants as random effects (model 3) to be a better fit for the data [$\chi (2)^2 = 17.90$, $p < .001$]. This showed that prosaccades were significantly faster than antisaccades ($\beta = -.09$, SE = .01, t = -9.40) and overall participants were slower to perform saccades after completing two initial than one cognitively effortful tasks ($\beta = .06$, SE = .02, t = 2.40). Further, it revealed an initial condition by task interaction; following the completion of two cognitively effortful tasks, prosaccades were faster than antisaccades (β = -.05, SE = .01, t = -4.00). Adding gAUC as a covariate to the model (4) revealed this to be a significantly better fit for the data [$\chi (4)^2 = 41.16$, $p < 2.49 \times 10^{-08}$]. An initial condition x task x OGTT interaction was observed (β = -.04, SE = .01, t = -4.80); those with poorer (high gAUC) relative to better glucose regulation (lower gAUC) performed slower in the antisaccade compared to prosaccade task, with this being stronger in those that completed two initially cognitively effortful tasks. Adding motivation and self-control to the model did not result in these being significant predictors of saccade RTs and thus did not improve model fit (p> .05).

Performance accuracy (rate of erroneous antisaccade responses)

Using GLMM and initially fitting a model with initial condition as a fixed effect and participant as a random effect showed initial condition to not be a significant predictor of erroneous responses in the antisaccade task [β= -.40, SE = .69, Z = - .58, p = .56]. Adding gAUC as a covariate produced a main effect of gAUC which approached significance [β= .38, SE = .21, Z = 1.76, p = .08] but no further significant main or interaction effects. Adding drink to the model as a fixed effect and motivation as a covariate observed no significant main or interaction effects (p > .05). Subsequently fitting a model with participant as a random effect and gAUC as a covariate revealed gAUC to be a significant predictor of directional errors irrespective of the initial tasks completed [β= .32, SE = .15, Z = 2.09, p = .04]. The relationship between directional error rate and gAUC was positive, indicating that having worse gluco-regulatory control (higher gAUC) resulted in more errors being committed in the AST. Further, we fitted a model with participants as random effects, initial condition as a fixed effect and both gAUC and self-control as covariates. This revealed self-control to be a significant predictor of directional error rate [β= -.50, SE = .21, Z = - 2.33, p

= .02] as well as gAUC [β= .50, SE = .19, Z = 2.60, p = .01]; those high in self-control and those with better glucose regulation produced fewer AS errors. The gAUC by self-control interaction was also significant [β = .03, SE = .01, Z = 2.35, p = .02]; those with better self-control and better glucose regulation performed fewer antisaccade directional errors (see Figure 5).

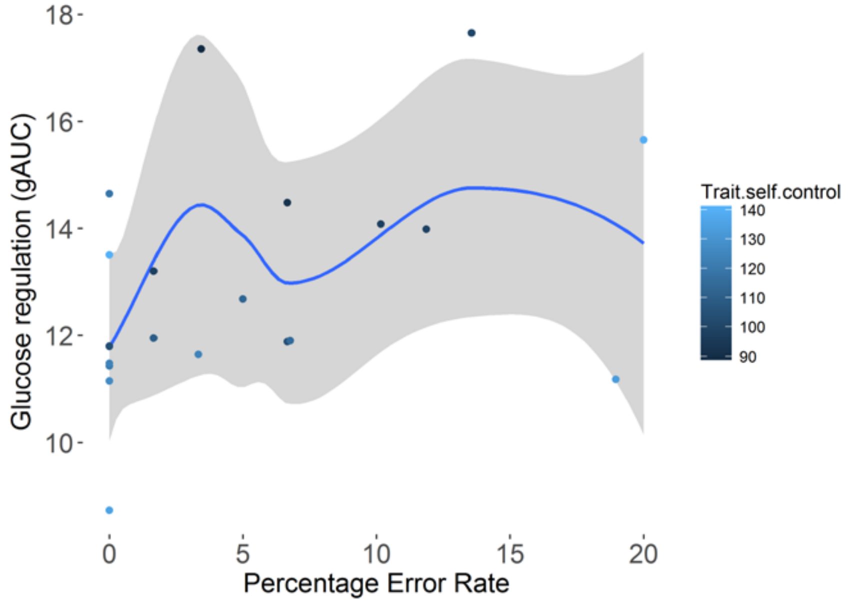

Figure 5: Rate of directional errors as a function of glucose regulatory control (gAUC) and self-reported levels of self-control.

Working memory

An initial correlation analysis revealed no significant relationship between gAUC and working memory span or response speed [all p > .05]. This was reinforced using linear modelling analysis; gAUC was not a significant predictor of WM span [β = -.09, SE = .10, t = -.86, p = .40] nor speed of responding [β = -.204.00, SE = 316.10, t = -.65, p = .53]. Adding self-control to the model as a covariate produced no significant main or interaction effects [all p > .05].

Stroop performance

There was an approaching significant negative correlation between gAUC and performance accuracy in the Stroop task for those that completed the incongruent version and exerted self-control [$r = -.56$, $p = .09$]; poorer glucose regulation (high gAUC) was associated with lower Stroop accuracy. This was not observed for the congruent (control) version of the task [$r = .27$, $p = .46$]. These correlations were examined further using linear modelling analysis. We initially fitted a model with participant as a random effect and initial condition as a fixed effect and then added gAUC as a covariate to the model. Initial condition was observed to be a significant predictor of performance accuracy [$\beta = 16.40$, SE = 3.28, $t = 4.99$, $p < 9.33 \times 10^{-05}$]; the congruent (control) task was performed more accurately than the incongruent version. Adding gAUC to the model revealed this to be a significant predictor of performance [$\beta = -3.87$, SE = 1.43, $t = -2.71$, $p = .02$]; those with a high gAUC (poorer glucose regulation) made more erroneous responses (less accurately). Further the gAUC x initial condition interaction was significant [$\beta = 4.02$, SE = 1.73, $t = 2.32$, $p = .03$]. Inspection of the means revealed that following the completion of the incongruent Stroop task, those with better glucose regulation (lower gAUC) performed the task more accurately and this approached significance [$\beta = -3.87$, SE = 2.00, $t = -1.93$, $p = .089527$]. gAUC did not significantly predict performance in the congruent Stroop task [$\beta = .15$, SE = .19, $t = .78$, $p = .46$]. Adding self-control to the model as a covariate produced no significant main or interaction effects [all $p > .05$].

Individual differences in self-control

A significant negative correlation between individual differences in self-reported levels of trait self-control and gAUC was observed (see Figure 6); those with low self-control had poorer glucose regulation (high gAUC) [$r = .47$, $p = .04$].

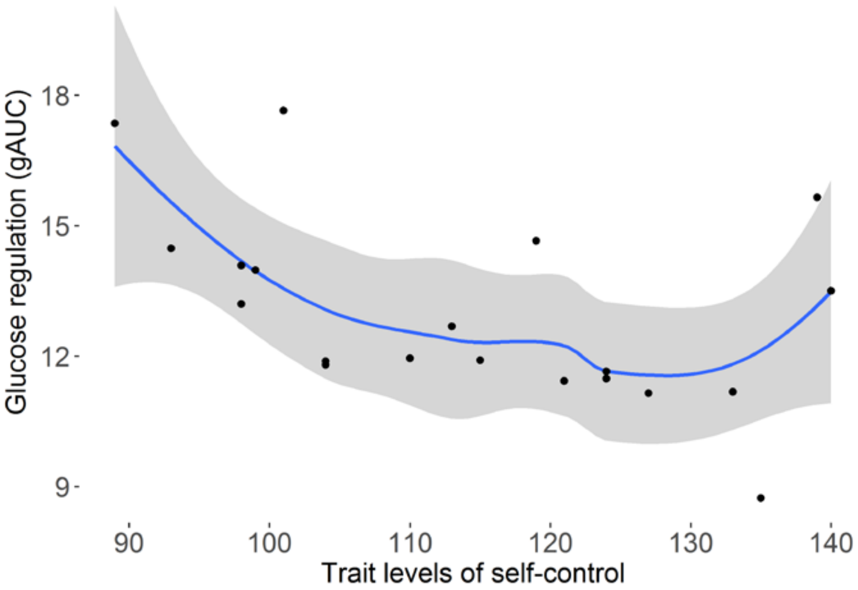

Figure 6: The relationship between gAUC (a measure of glucose regulatory control) and individual differences in self-control.

Discussion

The resource depletion theory (Baumeister, Vohs & Tice, 2007) posits that exerting self-control relies on a limited resource and consequently exercising self-control reduces the availability of the resource, weakening subsequent attempts at self-control. Previous research argued that glucose was the energy substrate responsible for the successful application of self-control (Gailliot et al., 2007). For example, investigations observed peripheral blood glucose levels significantly diminished following self-control exertion (e.g. Fairclough & Houston, 2004; Gailliot et al., 2007) and the consumption of a glucose drink ameliorated any subsequent deficiency in self-control performance (e.g. Gailliot et al., 2007; DeWall et al., 2008).

However, the findings of this study challenge these observations as – using a reliable portable finger prick measuring device - no significant reduction in peripheral blood glucose levels was observed over time following the completion of the tasks. This is in line with findings of more recent studies, which showed no significant changes in glycaemic response following the application of self-control (e.g. Kelly et al., 2015; Molden et al., 2012; Sanders et al., 2012). Further, irrespective of the initial tasks completed, consuming a 40g glucose drink - a comparable dose to that administered in previous studies (e.g. Gailliot et al., 2007; Wang & Dvorak, 2010; Denson, et al., 2010) – did not enhance self-control performance in the subsequent antisaccade task (Hallett, 1978). This supports a recent meta-analysis, which observed no direct relationship between self-control performance and glucose availability (Dang, 2016).

Motivation however was observed as a powerful predictor of performance in the antisaccade task; those high in motivation performed more accurately. For those low in motivation engaging in cognitively demanding tasks weakened performance in a subsequent cognitive task. Supporting previous findings in our lab (Kelly et al., 2015), high motivation maintained performance levels following prior exertion. This adds to the growing body of literature, which suggests that motivation plays a significant role in counteracting the effects of initial cognitive exertion on self-control performance (Klinger, 2013). In particular, the resource allocation account (Beedie & Lane, 2012) argues that resources will only be allocated to the completion of later cognitive tasks if the motivation to apply effort is high.

The current study also aimed to explore whether depletion effects in subsequent tasks are specific to self-control tasks or whether this can be extended more generally to the completion of cognitively effortful tasks. The results revealed that engaging in a working memory task resulted in weakened antisaccade performance for those low in motivation. This supports previous research by Shiv and Fredorkin (1999), which showed that completing an initial working memory task before a food selection task, resulted in participants exercising low self-control and selecting an unhealthy food product. More generally, this finding suggests that the depletion effects are not necessarily specific to tasks pertaining to self-control, but can be observed following performance of other executive function tasks (Bertrams, Baumeister, Englert & Furley, 2015).

However, we also observed restorative effects of motivation for those that initially completed one cognitively effortful task paired with a basic task. Specifically, level of motivation significantly predicted antisaccade error rate; those low in motivation performed more erroneously in the subsequent antisaccade task but having high motivation counteracted this.

Further a significant relationship emerged between glycaemic response and motivation for those that initially engaged in the working memory task paired with the more basic congruent Stroop task. High levels of motivation irrespective of drink, significantly predicted higher blood glucose levels at t3, after the completion of the saccade tasks. This is consistent with a recent study by Kazén, Kuhl and Leicht (2014), which observed an association between heightened levels of motivation and an increase in peripheral blood glucose levels. Kazén et al (2014) reasoned that when one is highly motivated, vigour in the form of energy – reflected by higher blood glucose levels - is injected into exerting effort and performing a task well.

This supports the resource allocation account (Beedie & Lane, 2012), which argues that when motivation is high, resources are allocated to subsequent tasks following prior exertion leading to successful exertion. When motivation is low, resources are not allocated and performance deterioration occurs. Thus one could speculate based on the results - which also are consistent with Kazén et al (2014) – that energy in the form of glucose increased and was allocated by those high in motivation leading to successful subsequent performance i.e. fewer errors in the antiscacade task. Although one cannot claim that the changes in glycaemic patterns that occurred in the periphery reflected those centrally, the portable finger-prick glucose monitoring devices have been reported to strongly correlate with AV blood measures (Dye et al., 2010). More research is needed to explore this further.

Although the current findings could be taken to support the shifting priorities account (Inzlicht & Schmeichel, 2012), this is a non-resource perspective and based on our observations that heightened glucose levels were paired with heightened motivation the current findings arguably fit more consistently with the resource allocation account (Beedie & Lane, 2012). This supports more recent evidence that shows motivation plays a key role in counteracting the temporary deficiency observed in the second of two sequential tasks (Lee, Chatzisarantis & Hagger, 2016).

Interestingly, the combination of initial tasks completed significantly predicted antisaccade performance. Specifically completing two tasks that were cognitively effortful (working memory and incongruent Stroop task) led to greater accuracy in the antisaccade task. This challenges the resource accounts and fits more consistently with the adaptation account (Helson, 1964). Based on the results one could speculate that initially completing two cognitively effortful tasks (working memory paired with incongruent Stroop task) allowed for task adaptation and resulted in an improved performance in the third task, namely the subsequent antisaccade task (Converse & Deshon, 2009; Dang et al., 2013). Previous research for example showed that completing two or more initially cognitively effortful tasks led to an enhanced or sustained performance on a subsequent task (e.g. Carter & McCullough, 2013; Graham & Bray, 2012; Xiao, et al., 2014) but completing one initially cognitively effortful task impaired performance on a subsequent task (Graham & Bray, 2012).

Additionally level of motivation had no modulating effect on antisacacde performance for those that completed two initially cognitively effortful tasks (working memory paired with incongruent Stroop task). Arguably as antisaccade performance was enhanced after completing two initially demanding tasks, level of motivation did not influence subsequent performance. This challenges Vohs et al (2012) as high motivation was observed to adversely affect performance of those completing three initially cognitively effortful tasks. This is an area that needs further exploration.

OGTT findings (gAUC)

The current study revealed that those with poorer glucose regulatory control (higher gAUC) performed more erroneously in the antisaccade task regardless of the initial tasks completed. There were no differences in performance in terms of depletion effect but interestingly the results showed that glucose tolerance affected self-control performance in general. Further, glucose regulatory ability was related to how well one performed in the incongruent version of the Stroop task; participants performed more accurately if they had better glucose regulatory control. Individual differences in self-reported self-control were also observed to be significantly related to glucose regulation; those with better glucose regulation were reported to have higher levels of self-control.

These findings support the previous literature suggesting a connection between a deficiency in one's ability to effectively process glucose in the body (Lamport et al., 2009) and symptoms of poor self-control. For example Dewall, Deckman, Gailliot and Bushman (2011) observed diabetic symptoms correlated well with aggressive type symptoms; a trait of poor self-control. Further, the literature consistently demonstrates that there is a connection between low levels of available blood glucose and poor self-control (Baumeister, 2014; Baumeister & Vohs, 2016). In the current study, the effect of glucose regulation on performance was not however extended to the working memory task (reverse digit span task) or basic cognitive tasks e.g. the prosaccade and congruent Stroop tasks. Glucose regulation appears to thus play a specific role in inhibitory processing and self-control ability (Gailliot & Baumeister, 2007).

To the author’s knowledge this was one of the few studies to have examined the role of glucose regulation on self-control performance in a sequential task paradigm. Although based on a small sample size it was arguably informative as it illustrated that subtle differences in glucose regulation even in a sample of healthy participants (Owen et al., 2013) influenced self-control performance; those with poorer glucose regulation performed a subsequent self-control task at a weaker level regardless of the initial tasks completed.

Limitations

Although we demonstrated differences in self-control performance based on motivation level, this was reliant on self-reported measures of motivation, which are limited due to their subjective nature. To strengthen this finding it will be beneficial for future research to actually manipulate levels of motivation to directly tap the relationship between motivation and self-control performance over time.

Furthermore, although the findings showed that completing two initially effortful tasks (working memory paired with incongruent Stroop task) led to a better antisaccade performance than completing one such task, supporting an adaptation account, one must consider that there is likely to be an optimal point at which adaptation is reached and performance declines. More investigations are needed to assess this is detail.

Conclusions

The present study observed motivation rather than glucose administration to be a significant predictor of antisaccade performance. Consistent with the resource allocation account (Beedie & Lane, 2012) those low in motivation displayed a temporary deficiency in self-control performance following prior exertion in a cognitively effortful task. Having high levels of motivation, however ameliorated this effect. Also consistent with this glucose levels were higher for those high in motivation after completion of the antisaccade task; resources were injected into task completion (Kazén et al., 2014).

Additionally, this study showed that resource depletion can be applied to other EFs as performing a working memory task resulted in a temporary weakening in antisaccade performance for those low in motivation. Interestingly and against expectations of the resource depletion theory, performance was enhanced in the later antisaccade task for those completing two initially cognitively effortful tasks (working memory task paired with incongruent Stroop task) compared to one (working memory task paired with congruent Stroop task). This finding fits consistently with the adaptation account, which argues that the more tasks one engages in, the greater the improvement in subsequent performance. This study was therefore informative as it illustrated that the number of consecutive tasks one completes modulates performance outcome and the extent motivation level restores performance. Further, individual differences in glucose regulation predicted self-control performance in both the incongruent Stroop and antisaccade tasks. More research is needed to examine the resource allocation account in comparison to the adaptation account with the administration of more sequential cognitively effortful tasks.

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Paper four: Completing two consecutive self-control tasks successfully: does prior fasting duration modulate any glucose effects or does motivation play a role?

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Abstract

Research typically shows that performing an initial self-control task adversely affects performance in a subsequent self-control task. The strength model of self-control posits that this impairment arises from a depletion of resources, such as glucose. The current study explored whether fasting duration prior to the session moderated any glucose effects on self-control performance. As recent research and theories such as the resource allocation account suggest that motivation is a more powerful predictor of self-control performance, motivation level was also measured as a potential moderator of self-control in addition to beliefs about willpower capacity and trait levels of self-control. The current investigation administered a Stroop (incongruent vs. congruent/control) task followed by an antisaccade (and prosaccade) task to participants that engaged in either a two or four hour fast. Participants received a 40g glucose or placebo drink after Stroop task completion. The results of the study challenge the strength model of self-control, as exerting self-control in an initial task led to no deterioration in performance in the antisaccade task. Additionally, neither glucose administration, or fasting duration moderated self-control performance over time. However, motivation was a significant predictor of the rate of erroneous responses in the antisaccade task irrespective of initial level of self-control exertion; highly motivated participants committed less directional errors. This was against expectations of the resource allocation account. We concluded that the larger sample size implemented might have accounted for these findings along with limitations of the Stroop task and type of manipulation check used. Further research is required to clarify this.

Key words: self-control, fasting, glucose, motivation

Completing two consecutive self-control tasks successfully: does prior fasting duration modulate any glucose effects or does motivation play a role?

Self-control is involved in the regulation of behaviour and suppression of impulsive responses (Gailliot et al, 2007; Baumeister, Vohs & Tice, 2007). It is exercised regularly every day and positively affects general health and wellbeing (Hoffman, Baumeister, Foerster, & Vohs, 2012). Evidence shows that engaging in two sequential self-control tasks is an effortful process and individuals typically perform well in the first task but display a temporary deficiency in performance in the second. The resource depletion theory/strength model of self-control (Baumeister et al, 2007) posits that this is because self-control relies on the availability of a limited energy resource and applying self-control reduces this resource resulting in less being available for the successful application of self-control in subsequent tasks. This situation of diminished resources and thus weakened performance was termed ‘ego depletion’ (Baumeister & Vohs, 2016). Such weakened performance has been replicated in numerous studies using a wide variety of tasks within a sequential two task self-control depletion paradigm (see meta-analysis by Hagger, Wood, Stiff, & Chatzisarantis, 2010) where an initial self-control task is administered followed by a subsequent self-control task.

The energy resource that has been linked to self-control is glucose (Gailliot et al., 2017). The strength model/resource depletion theory of self-control (Baumeister et al., 2007;) argued that self-control deterioration stems from a reduction in the availability of glucose (Gailliot et al., 2007). Indeed, the brain has a high metabolic rate and its metabolism is almost entirely restricted to oxidative utilization of glucose (Amiel, 1994). Over the last thirty years, a large body of literature has demonstrated beneficial effects of acute glucose administration on different aspects of cognition in various populations (see Sünram-Lea & Owen, 2017 for a recent review). Compared to other cognitive tasks, the energy cost for effortful, controlled or executive processes appears to be significantly higher than that for automatic or reflexive processes (Gailliot & Baumeister,. 2007). Indeed, lowered peripheral glucose levels following performance of cognitively demanding tasks have been reported (Scholey, Harper & Kennedy, 2001; Fairclough & Houston, 2004). It has been argued that such fall in plasma glucose could reflect a more efficient transfer of glucose to the brain which in turn results in increased provision centrally (Scholey, Harper & Kennedy, 2001). However, more recent studies have failed to replicate such fall in peripheral blood glucose levels following performance of cognitively demanding tasks; i.e. application of self-control (Lange & Eggert, 2014; Kelly, 2015). Moreover, although glucose administration has been shown to enhance performance in a subsequent self-control task following prior exertion (Gailliot et al., 2007; DeWall, Deckman, Gailliot & Bushman, 2011; Wang & Dvorak, 2010), more recent investigations failed to observe a restorative effect of glucose administration on subsequent performance (e.g. Lange & Eggert, 2014; Kelly et al, 2015; Kelly, Sünram-Lea & Crawford., in preparation). Together, there is evidence that challenges the role of glucose in self-control (Kurzban, 2010; Dang, 2016).

However, it is important to note that previous studies differed in terms of the amount of glucose administered (amounts 25g - 50g) and the degree of fasting implemented prior to testing. More specifically**,** the length of fasting differed between studies ranging from 0h to 12h (overnight fast) and this might have contributed to the equivocal findings (see table 1). The current study addressed whether fasting duration influenced the lack of any observed glucose effects on performance. In this investigation we examined the effects of glucose administration on self-control performance, comparing participants that fasted for 2 hours prior to the session to those that fasted for 4 hours. Indeed, if there are differences in the effects of blood glucose availability on self-control performance depending on the fasting duration then this could arguably provide more information about the relationship between glucose availability and self-control.

Table 1

A summary of the fasting duration used in previous studies that examined the relationship between blood glucose availability and sequential self-control performance

Fasting duration (hours)	Studies
0*	Masicampo and Baumeister (2008); Gailliot, Peruche, Plant and Baumeister (2009); DeWall, Baumeister, Gailliot and Maner (2008); a number of Gailliot et al's (2007) glucose studies; Sanders, Shirk, Burgin, and Martin (2012); Wang and Dvorak (2010)
1	Fairclough and Houston (2004)
1.5	Lange and Eggert (2014): study 1
2	Lange and Eggert (2014): study 2
3	Gailliot et al (2007); Denson, von Hippel, Kemp and Teo (2010); DeWall, Deckman, Gailliot and Bushman (2011); DeWall, Baumeister, Stillman and Gailliot (2007); Dvorak and Simons (2009); Hagger and Chatzisarantis (2013); Carter and McCullough (2013); Leung, Stone, Lee, Seidman, & Chen, (2014)
4	Molden et al (2012)
Overnight fast	Boyle, Lawton, Allen, Croden, Smith & Dye (2016)

*Either 0 hours of fasting or limited information was reported in the paper.

Moreover, previous evidence has shown that rinsing the mouth with a glucose solution, which would have had no effect on circulating glucose levels, significantly improved self-control performance (Molden et al., 2012; Sanders et al., 2012; Hagger & Chatzisaratis, 2013). The absence of a peripheral metabolic action in these circumstances raises the possibility of a centrally mediated effect. For example glucose might have a motivational influence on self-control performance, with the sensing of glucose in the mouth activating brain areas associated with motivation (Chambers, Bridge & Jones, 2009). More recent research has shown that motivation had an influential effect on sequential self-control task performance with high levels of motivation counteracting any temporary deficiency in performance in a second act of self-control following prior exertion (Muraven & Baumeister, 2000; Inzlicht & Schmeichel, 2012; Inzlicht, Berkman & Elkins-Brown., 2016; Kelly et al., 2015). The resource allocation account (Beedie & Lane, 2012) supports the role of motivation in self-control. The theory suggests that having the motivation based on one's interest and enjoyment in completing the self-control tasks, leads to the assignment of resources to the task and as a result the successful completion of the task irrespective of any previous application of self-control. Similarly the shifting priorities/ process model supports a motivational perspective - but does not draw on a role for a resource - and posits that a weakened performance in a second task of self-control stems from an alteration or shift from one having the motivation to willingly exert self-control in the first task to this being reduced in the second task (Inzlicht & Schmeichel, 2012; Inzlicht et al., 2016; Inzlicht, Schmeichel, & Macrae, 2014). Consequently, if one is highly motivated to engage in the second task, self-control would be applied successfully in the subsequent task and performance deterioration counteracted.

In addition to the role of motivation, previous research has also observed differences in one's vulnerability to self-control deficiency following prior exertion depending on whether one does or does not hold the belief that self-control relies on a limited resource. For example Job, Dweck, and Walton (2010) revealed that naturally holding the view that self-control was limited (vs. limitless) led to the typical response trajectory posited by the resource depletion theory; a temporary deficiency in performance in the second of two concurrent self-control tasks. This was not observed in those that believed self-control was not limited.

Miller, Walton, Dweck, Job, Trzesniewski, & McClure (2012) observed that during a twenty minute working memory task (divided into two sections), those led to believe that willpower was limited, showed a temporary deterioration in performance in the second part of the task. However, participants that were exposed to the idea that self-control was unlimited showed an improved level of performance in the second part of the task. Further, a study by Vohs, Baumeister, and Schmeichel (2012) revealed that those who believed self-control was limited displayed an enhanced level of self-control performance in a second task following initial exertion. This was not extended to the completion of four consecutive self-control tasks.

Job, Walton, Bernecker, and Dweck (2013) explored whether holding a limited resource view moderated the potential ameliorating effects of glucose administration on self-control ability in the second of two sequential self-control tasks. The authors observed that those biased to believing self-control was limited performed at a weaker level following the placebo relative to glucose drink. Thus glucose administration enhanced performance in the second task, but only for those that held a limited resource belief about self-control ability. For the purpose of this investigation we explored whether Job et al.'s (2013) findings could be replicated by examining whether individual differences in one's pre-existing views – assessed using a self-report questionnaire – about the capacity of self-control, moderated the extent that glucose relative to placebo consumption restored self-control performance following prior exertion.

The current investigation

In summary, we conducted a study, which manipulated fast duration (2 versus 4 hours) to assess whether length of fasting time moderates the potential effects of glucose administration on sequential self-control task performance. Further, we explored whether holding a limited compared to unlimited resource view – as Job and colleagues (Job et al., 2010; Job et al., 2013; Job, Bernecker, Miketta, & Friese, 2015) and Miller et al (2012) previously examined - moderated the extent that a glucose drink ameliorated any temporary reduction in self-control. Motivation level was also measured to examine whether – as more recent theories and findings on self-control suggest – level of motivation influences the extent that impairment in self-control performance occurs in a second task.

Additionally, previous studies which explored self-control performance over time have been challenged for relying on small sample sizes and therefore lacking in power (see Carter & McCullough, 2014). We addressed this by recruiting a larger sample of participants (N = 120).

Method

Design

The current study employed a 2 (initial condition; self-control/depletion vs. control) x 2 (drink condition; 40g vs. 0g. glucose) x 2 (fasting duration; 2 vs. 4 hour fast) x 2 (saccade task; prosaccade, antisaccade) x 3 (blood glucose reading; time 1, time 2, time 3) mixed-factorial design with repeated measures for saccade task and glycaemic response reading.

Participants

One hundred and twenty healthy young adult volunteers (36 males & 84 females) aged between 18-35 years (M = 20.45, SD = 3.10) were recruited. Individuals were screened and excluded if they had Diabetes Mellitus, had any food intolerance or allergic reaction to food or substances that contain phenylalanine, and if female, were pregnant, seeking to become pregnant or lactating. A power analysis based on previous evidence indicated that with an alpha level of 0.05 a sample size of 120 would be adequately powered (0.83).

Materials

Initial depletion task: Stroop task (Stroop 1935): A computerised version of Wallace and Baumeister's (2002) Stroop task was administered. Participants responded to the ink colour of a series of colour words (red, blue, green, purple & yellow) as precisely and as rapidly as possible by pressing certain keys on the keyboard, as well as stating their response out loud. The duration of the task was approximately 4 minutes 30 seconds (135 colour words). We administered a manipulation check, which measured four areas of performance – how frustrating the task was to complete, amount of effort exerted, how pleasant one found the task and level of tiredness felt after task completion (Denson et al., 2011) – to compare whether there were any self-reported differences between the completion of the congruent and incongruent tasks.

Control (congruent): Colour words were matched to the ink colour they were written in.

Self-control: This was an incongruent colour-naming task in which the colour words and the ink colours of the words were mismatched. An additional instruction was included, which required participants to ignore the rule of stating the ink colour of the word when responding to 'red' and state the written word.

Dependent measure of self-control (second task): Saccade tasks (Hallett, 1978): Participants completed a series of trials (30 for each task) in which a dot was presented on a computer screen to the left or right hand side. Eye-movements were recorded via a camera

(Eye Link II) attached to a headset, which was worn. Participants were sat 60cm away from the computer screen. Overlap versions of both tasks were used in which a fixation cross was presented first in the centre of the screen and the target then appeared, while the fixation cross remained.

Prosaccade task: This required no inhibition or self-control; participants were instructed to direct their eyes towards the green dot. The prosaccade task was completed to assess whether the potential adverse effects of engaging in an initial self-control task applied to saccade tasks in general or whether it was unique to tasks that required self-control (i.e. the antisaccade task).

Antisaccade task: Participants were instructed to direct their eyes away - and to the opposite side of the screen – to the green dot as quickly and as accurately as possible.

Limited resource view questionnaire (Job et al., 2013)

Participants answered a series of 12 questions, which provided an overall indication of how resource limited willpower/self-control was considered to be. Self-reported responses were made using a six-point Likert scale and ranged from ‘strongly agree’ to ‘strongly disagree’. Statements that required a response included ‘After a strenuous activity, you feel energized for further challenging activities’ (limitless resource view) to ‘After a strenuous mental activity, your energy is depleted and you must rest to get it refuelled again’ (limited resource view). Responses were scored so that a higher value was associated with the belief that self-control has limited capacity.

Blood glucose level measurements

Peripheral levels of blood glucose were measured using the ExacTech glucose measuring device at baseline, after engaging in the Stroop task and after completion of the saccadic eye movement tasks. The device is deemed to have high measurement sensitivity (Rebel, Rice & Fahy, 2012) with a recent study observing a strong relationship between glucose measured in the capillary via a finger prick and arteriovenous (AV) blood (Dye et al., 2010).

Intrinsic Motivation Inventory (IMI) [McAuley, Duncan & Tammen, 1989]

Self-assessed levels of intrinsic motivation were recorded with a 36 item IMI. Participants made their responses using a 7-point-Likert scale, with answers ranging from 'not at all true' to 'very true'. Example statements that required a response included, 'I enjoyed doing this activity very much', 'This activity was fun to do', 'I did this activity because I wanted to' and 'I would be willing to do this again because it has some value to me'. Responses were then gathered to provide an overall assessment of how motivated participants were to complete the saccade tasks.

Trait levels of self-control

Using Tangney, Baumeister and Boone's (2004) 36 item self-control questionnaire participants were asked to rate statements such as 'I have a hard time breaking bad habits', 'I engage in healthy practices' using a 5-point-Likert scale that ranged from 1 = '*not at all like me'* to 5 = '*very much like me*'. The answers were collated to provide an average overall score for each participant.

Drink administration

Following a double-blind procedure, participants were randomly assigned to receive a 40g glucose (made with glucose/dextrose power, 250ml of water and 2 tsps. of unsweetened lemon juice) or 0g glucose/placebo (made with 5 Sweetex tablets, water and 2 tsps. of unsweetened lemon juice) drink, which were presented in clear plastic cups. Both were matched for sweetness and a sensory evaluation of the drinks found no differences in the perceived taste of the two drinks [$\beta = -.07$, $SE = .26$, $t = -.26$, $p = .80$].

Procedure

All participants were required to attend one experimental testing session, which lasted approximately 60 minutes. Prior to the experimental session, participants were instructed to fast (refrain from consuming any food or drink except water) for either 2 or 4 hours (manipulation of fasting duration). At the beginning of the session, participants were asked some demographic questions (regarding their age, height and weight) and asked to sign an informed consent sheet. Baseline blood glucose measurements were taken. Participants then engaged in either an incongruent (self-control/depletion) or congruent (control) Stroop task. A second blood glucose measurement was taken. Prior to the eye movement tasks and following a double blind procedure participants consumed either a 40g glucose or placebo/0g glucose drink. After a period of 15 minutes – to allow for glucose absorption – the prosaccade followed by the antisaccade tasks were then completed, followed by the final blood glucose measurement. The limited and self-control questionnaires and the intrinsic motivation inventory (IMI) were then administered before participants were thanked and fully debriefed.

Results

Statistical analysis

We calculated saccade response times (RTs) as the period between the onset of the target and the beginning of the first saccade either towards (for the prosaccade task) or away from the target (for the antisaccade task). Saccades with an amplitude of less than 2° and a speed of below 80ms or above 500ms (as these are considered to be early or late saccades) were removed from the analysis. Errors were only committed in the antisaccade task and examined by extracting the number of erroneous responses (incorrect saccades made towards rather than away from the target) compared to the number of correct responses made.

Saccade performance was analysed with linear mixed effects modelling (for saccade response time) and generalised linear mixed effects modelling (for correct compared to erroneous antisaccade responses) using R (R Core Team, 2015) and the package lme4 (Bates, Maechler, Bolker, & Walker, 2014). In particular a series of separate models were created for the two parameters of saccade performance; response time (RT) and erroneous relative to correct responses (for the antisaccade task only). Participants completed 30 trials for each saccade task and thus to account for individual variation we included participant in every model as a random effect (Winter, 2013). As only one item (a green dot) was used across both saccade tasks and the presentation of the target was randomised, item was not included as a random effect. We then ran through a series of models, adding saccade task (for response times only), initial condition (self-control vs. control), fasting duration (4 vs. 2 hour) and drink (glucose vs. placebo) as fixed effects. Self-reported levels of motivation, self-control and one's beliefs about self-control were all added as covariates to the models to assess whether differences in these measures moderated any observed effects that drink, initial task or fasting duration had on saccade performance (reaction times and/or errors) or whether they were significant predictors of performance irrespective of fixed effects.

Similarly, changes in glycaemic response patterns over time were analysed using linear modelling, treating participants as random effects and initial condition, fasting duration, drink condition and time of measurement (time one/ baseline, time two/ after the completion of the Stroop task & time three/ after saccade task completion) as fixed effects.

Motivation was included as a covariate to examine whether differences in self-reported levels significantly predicted glycaemic response.

Manipulation check for the Stroop task (initial measure of self-control)

Using general linear modelling analysis we explored whether self-ratings of effort expended, how pleasant, tired, frustrating the initial Stroop task was to complete, differed based on whether the control (congruent) or self-control (incongruent) version was completed. The effect of initial task on level of tiredness after task completion approached significance [F (1, 118) = 3.338, p = .07021]; participants reported to be more tired after completing the incongruent than congruent Stroop task. Level of effort expended differed based on the initial task [F (1, 118) = 8.986, p = .003318]; more effort was exerted in the incongruent than congruent task [β = 0.8833, SE = 0.2947, t = 2.998, p = .00332]. Further, how frustrating the initial tasks were to complete differed [F (1, 118) = 26.13, p = .000]; the incongruent Stroop task was rated as 1.50 more frustrating to complete than the congruent (control) version of the task [β = 1.5000, SE = .2935, t = 5.111, p = .000]. However, self-reported levels of task pleasantness did not differ by initial task [β = .0500, SE = .2069, t = .242, p = .809].

Stroop task accuracy: Initial task predicted performance accuracy [F (1, 118) = 65.64, p = .000]; applying self-control in the incongruent Stroop task resulted in participants performing with on average 13.399% less accuracy than participants that completed the control version [β = - 13.399, SE = 1.654, t = -8.102, p =. 000].

Saccade performance

Saccade response time (RT)

We initially fitted a null model, adding participant as a random effect. We then fitted a number of separate models and compared the different models using the likelihood ratio test. A comparison of the null model to a model fitted with saccade task as a fixed effect showed that type of saccade task significantly predicted response time ($\chi\ (1)^2$ = 1041.60, p = 2.2 x $10^{-16)}$; the prosaccade task was performed on average 53.20 msecs faster than the antisaccade task [β = - 57.26, SE = 1.71, t = -33.5]. Building the model further and including initial task as a fixed effect did not improve the model fit, nor did adding drink, fasting duration, motivation, beliefs about willpower and trait self-control ($p > .05$). Overall, examining saccade response times, results revealed that the antisaccade task was completed at a slower rate than the prosaccade task irrespective of the added fixed effects and covariates.

Correct vs. erroneous AS responses

A model with participant as a random effect and fixed effect for initial task (self-control vs. control) did not significantly predict erroneous AS responses [β = - 0.1571, SE = 0.2284, Z = - 0.688, p = .492]. Adding drink as a fixed effect did not reveal any significant effect of drink [β = - 0.21197, SE = 0.31975, Z = - 0.663, p = .507] nor a significant drink x initial task [β = 0.03955, SE = 0.45486, Z = - 0.087, p = .931] interaction on erroneous AS response rate. Building on the model and adding fasting duration, and then later motivation, trait self-control, and beliefs about willpower capacity produced no further significant effects or interactions [$p > 0.05$].

We then explored models fitted with various combinations of fixed effects and covariates. A model fitted with participant as a random effect, fasting duration as a fixed effect and motivation as a covariate revealed motivation to be a significant predictor of performance regardless of fasting duration [β = - 0.5571, SE = 0.2745, Z = - 2.029, p = 0.0424]; less erroneous responses were made as motivation increased, those low in motivation committed more AS errors (figure 1). Fasting duration did not significantly predict error rate [β = - 2.5582, SE = 1.6796, Z = - 1.523, p = 0.1277] nor was there a significant motivation x fasting duration interaction [β = 0.5806, SE = 0.3744, Z = 1.551, p = 0.1209].

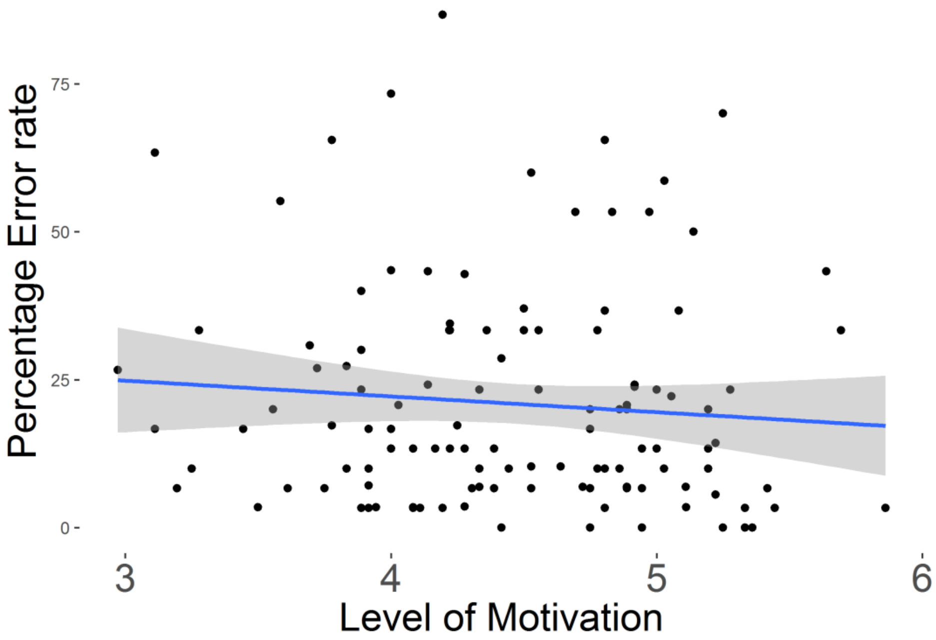

Figure: Rate of errors in the antisaccade task as a function of motivation level

Glycaemic response

Time of blood glucose measurement [F (2, 232) = 118.397, p = .000] and drink [F (1, 116) = 36.192, p = .000] both significantly predicted glycaemic response and there was a significant drink by time of measurement interaction [F (2, 232) = 123.775, p = .000]. Adding fasting duration (2 versus 4 hour fast) to the model did not predict glycaemic response [F (1, 112) = .985, p = .323], nor did adding the type of initial task completed (control vs. self-control) predict glycaemic response patterns [$F(1, 116) = .538$, $p = .465$]; there were no differences in blood glucose levels after initially exerting self-control relative to performing a control task. However, examining the time by drink interaction further, this revealed that 40g glucose administration led to a higher blood glucose reading at time three [$F(1, 116) = 137.308$, $p = .000$]. The relationship was positive indicating that readings were 2.56 mmol/L higher after glucose than placebo consumption [$\beta = 2.556667$, SE = .285027, $t = 8.970$, $p = .000$]. Following placebo administration there was a significant effect of time [$F(2, 116) = 6.321$, $p = .002$], indicating differences between measurement time two and three; blood glucose levels were significantly lower at time three than two [$\beta = .360000$, SE = .128039, $t = 2.812$, $p = .006$].Further, we added self-reported levels of motivation as a covariate to the model, which revealed no effect of motivation [$p > .05$].

Discussion

The current study examined whether completing an initial self-control task (incongruent Stroop task) produces a temporary deterioration in performance in a second self-control task (the antisaccade task). We assessed whether glucose relative to placebo administration counteracted any temporary deficiency in self-control performance and also whether fasting duration (2 versus 4 hours), level of motivation and beliefs about self-control moderated performance.

Against expectations of the strength model of self-control (Baumeister et al., 2007), no temporary deficiency in one's ability to apply self-control in the antisaccade task was observed following the completion of the initial Stroop task that required self-control relative to the control task. Further, no drink effects on self-control exertion were reported; glucose relative to placebo consumption did not enhance self-control performance in the antisacacde task following the initial application in the Stroop task. Additionally, no significant reduction in peripheral levels of blood glucose was observed following the exertion of self-control in the initial task. The only reduction observed was following placebo administration at the end of the test session (following antisaccade task performance) where levels fell irrespective of the initial task completed. These observations challenge the earlier literature conducted by Gailliot and colleagues (Gailliot et al., 2007) but supports more recent findings which observed no relationship between glucose administration and self-control ability (Molden et al., 2012; Sanders et al., 2012; Boyle et al., 2016; Kelly et al., 2015; Dang, 2016).

Moreover, responding to our earlier findings (Kelly et al., 2015) of no glucose effects, we examined the moderating effects of fasting duration on self-control performance. The results showed that amount of prior fasting had no effect on self-control performance over time. Therefore it is difficult to conclude that fasting duration and thus the availability of blood glucose were strong predictors of self-control performance, thus adding to the current inconsistent research on the relationship between fasting duration and cognition (Benau et al., 2014).

Implementing a fasting duration has however been previously criticised. Specifically, Kurzban (2010) argued that if glucose is the fuel responsible for self-control one should observe a reduction in blood glucose levels regardless of whether participants have fasted. However if a fasting duration is not implemented glycaemic response would be indicative of one’s prior food consumption. Internal mechanisms keep glucose levels stable and the longer one fasts for the greater the likelihood that these internal mechanisms become more pronounced. Therefore with a fasting duration, a clearer picture of glycaemic response patterns can be obtained. Thus despite Kurzban’s (2010) claims, an initial baseline fasting duration of blood glucose would arguably account for individual differences in initial level of energy input.

Further, results showed that motivation was a significant predictor of error rate in the antisacade task; more erroneous relative to correct responses were committed by those low in motivation. This was observed irrespective of the initial task completed and therefore challenged our expectations based on the previous literature, which showed that motivation moderated performance only for those that had applied self-control in an initial task (Lee, Chatzisarantis, & Hagger, 2016)

The resource allocation account (Beedie & Lane, 2012) posits that performance in the second of two sequential self-control tasks deteriorates due to a lowering in motivation – stemming from a lack of interest or enjoyment in the task - and thus a reluctance to invest resources in the task. If however a task is viewed to be interesting or important (i.e. having high motivation) one will perform well and apply resources despite previous self-control exertion. The shifting priorities account (Inzlicht & Schmeichel, 2012) argues that a weakened performance in a second task stems from an altering perspective, from engaging in an initial task that one feels they have to complete to wanting to only engage in subsequent tasks (i.e. the second task) that are enjoyable. If level of interest is not maintained in the second task, impairment in performance in the second task is observed. Despite providing limited support for these accounts, motivation level still had an impact on the successful application of self-control in the antisaccade task; those high in motivation made less erroneous antisaccade responses.

Potential reasons for these inconsistent findings might stem from the amount of self-control that one actually expended in the initial self-control task compared to control task (Lee et al., 2016). The control task we implemented was somewhat monotonous and thus self-control might have been applied through one continually persevering on the task. If this is the case, all participants may have applied some level of self-control in the initial task, with motivation level then moderating subsequent self-control performance in the antisaccade; those low in motivation displaying the typical weakening in self-control.

The manipulation check however showed the self-control task to be more frustrating to complete and requiring more effort. And differences in reported levels of tiredness based on the initial task were found. However it is important to note that the manipulation check is not a measure for the degree of self-control that was actually used (Lee et al., 2016). An ego depletion scale might have been more effective to assess the extent that self-control was applied in the initial task compared to control task (Chatzisarantis & Hagger, 2015; Lee et al., 2016).

Further, employment of the Stroop task has previously produced inconsistent findings. Although having been frequently used in the literature as an initial self-control task, with results showing that performing the Stroop task produces a temporary deterioration in subsequent self-control ability (Hagger et al., 2010; Wallace & Baumesiter, 2002) a meta-analysis by Carter, Kofler, Forster, & McCullough (2015) provided limited support that the ego depletion effect extends successfully to completion of the Stroop task. This might account for why we observed no antisaccade performance differences based on the type of Stroop task initially completed.

The current findings add to the existing debate surrounding the tenability of the ‘ego depletion’ effect; whether it actually occurs and the factors that moderate the effect i.e. the temporary deterioration in self-control performance (Carter &McCullough, 2014; Carter et al., 2015). Publication bias arguably has inflated one’s believe in the ego depletion effect with significant results being favoured rather than null findings (Carter &McCullough, 2014; Carter et al., 2015). Consequently more recently published research has failed to replicate the ego depletion effect (e.g. Xu et al., 2014; Lurquin, Michaelson, Barker, Gustavson, von

Bastian, Carruth, & Miyake, 2016; Hagger et al., 2015). Thus the study supplemented this area of research.

However some have questioned the size of the samples previously used to examine sequential self-control task performance and particularly those that explored the effects of glucose on self-control performance; prior research predominantly relied on smaller samples. This has led some to suggest that the ego depletion effect was restricted to smaller studies, which were underpowered and produced larger effect sizes in support of an effect, thus running a risk of a type one error (Carter & McCullough, 2014; Carter et al., 2015). The current investigation employed a larger sample (N = 120) and observed limited support for the observation that self-control performance weakens over time, thus supporting the argument that the ego depletion effect is limited to studies, which use smaller samples. More research with larger sized samples like this one are needed to further examine whether previous findings on the ego depletion effect can be replicated.

Moreover, we observed no evidence that one’s limited beliefs about willpower influenced self-control performance, which challenges expectations based on previous research, particularly by Job and colleagues (Job et al., 2010; Job et al., 2013; Miller et al., 2012). Nor did trait levels of self-control predict self-control ability in the antisaccade task following prior exertion. The findings on the moderating effects of trait self-control however have in the past been mixed (Imhoff, Schmidt, & Gerstenberg, 2013; Salmon, Adriaanse, De Vet, Fennis, & De Ridder, 2014), thus there is inconsistent evidence to show that one’s inherent ability to apply self-control positively influences self-control performance over time.

In conclusion, the results of the present investigation add to the debated area of research which attempts to address why self-control performance typically diminishes over time and addressed a research gap by testing a larger sample of participants. We observed motivation predicted the rate of erroneous responses in the antisaccade task, irrespective of initial task completed, drink consumed or prior fasting duration. This challenges the strength model of self-control and resource accounts, that initially exerting self-control produces deterioration in subsequent self-control performance, and that a glucose drink counteracts this effect. The findings provide partial support for a motivational account (e.g. resource allocation and shifting priorities accounts) as motivation predicted antiscacade performance albeit irrespective of initial level of self-control expended. However although many previous studies have employed the Stroop task as the initial self-control task (Hagger et al., 2010), the inconsistent results might stem from the difficulty in measuring how much self-control was exerted in the self-control version of the task relative to the control task, particularly when relying solely on a manipulation check to assess this. Therefore other methods to assess the extent of self-control exertion are required.

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Paper five: A temporary deficiency in self-control: Can heightened motivation overcome this effect?

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A temporary deficiency in self-control: Can heightened motivation overcome this effect?

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Abstract

Self-control is important for everyday life and involves behavioral regulation. Self-control requires effort, and when completing two successive self-control tasks, there is typically a temporary drop in performance in the second task. High self-reported motivation and being made self-aware somewhat counteract this effect—with the result that performance in the second task is enhanced. The current study explored the relationship between self-awareness and motivation on sequential self-control task performance. Before employing self-control in an antisaccade task, participants initially applied self-control in an incongruent Stroop task or completed a control task. After the Stroop task, participants unscrambled sentences that primed self-awareness (each started with the word "I") or unscrambled neutral sentences. Motivation was measured after the antisaccade task. Findings revealed that, after exerting self-control in the incongruent Stroop task, motivation predicted erroneous responses in the antisaccade task for those that unscrambled neutral sentences, and high motivation led to fewer errors. Those primed with self-awareness were somewhat more motivated overall, but motivation did not significantly predict antisaccade performance. Supporting the resource allocation account, if one was motivated—intrinsically or via the manipulation of self-awareness—resources were allocated to both tasks leading to the successful completion of two sequential self-control tasks.

Descriptors: Self-control, Self-awareness, Motivation, Antisaccade task

Self-control is the ability required to override or inhibit an automatic/impulsive response for another, involved in successful behavioral regulation (Baumeister, Heatherton, & Tice, 1994). Self-control can be applied to many situations, such as suppressing emotions, avoiding distractions at work (e.g., checking social media; Otten et al., 2014). Self-control is employed regularly every day, and research has estimated that we use self-control processes approximately 3 to 4 h each day (Hoffman, Baumeister, Foerster, & Vohs, 2012). It is necessary for human social interaction, and there are clear detrimental effects of self-control failure such as crime, obesity, smoking, and drug problems (Hagger, Wood, Stiff, & Chatzisarantis, 2010).

Despite its importance and regular use, several studies have shown that engaging in self-control is effortful, and when completing two sequential self-control tasks, the first task is usually performed well but a temporary deterioration in performance in the second occurs (Hagger et al., 2010). Studies typically employed a sequential self-control depletion paradigm in which two concurrent self-control tasks were completed. Frequently employed tasks include the incongruent Stroop (1935) task, a thought suppression task, an attention control video task, and an erasing letters task (Carter, Kofler, Forster, & McCullough, 2015; Hagger et al., 2010). We recently implemented another feasible measure of inhibition—the antisaccade task (Hallett, 1978)—into a sequential self-control task paradigm (Kelly, Sünram-Lea & Crawford, 2015).

The strength model/resource depletion theory of self-control (Baumeister, Vohs, & Tice, 2007) suggested that the temporary deterioration in task performance following self-control exertion stems from a depletion of limited energy resources. Performing a task necessitating self-control diminishes those resources, and consequently fewer resources are available, resulting in weakened subsequent self-control performance.

Glucose was proposed as the relevant physiological energy resource following observation that peripheral glucose levels were significantly reduced following self-control exertion (Fairclough & Houston, 2004) and that glucose relative to placebo administration restored subsequent self-control performance following prior exertion (Gailliot et al., 2007). However, recent findings have failed to replicate this, challenging the relationship between glucose availability and self-control performance (Dang, 2016; Kelly et al., 2015; Kurzban, 2010; Kurzban, Duckworth, Kable, & Myers, 2013; Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012). Although these findings do not necessarily imply that there is no temporary shortage in the energy and more specifically

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glucose supply centrally, other factors appear to play an important (but not mutually exclusive) role.

For example, level of motivation may be an important moderating factor in self-control inasmuch as it might ameliorate any self-control deficiency following prior engagement. That is to say, self-control is a motivated resource, and motivation determines the effort and time spent on certain tasks/behaviors (Salamore, Correa, Farrar, & Mingote, 2007). Supporting this, administering a monetary incentive for task completion or being told that the tasks were important resulted in an enhanced level of performance in a second self-control task following initial exertion (Muraven & Slessareva, 2003). Moreover, we previously observed that high levels of self-reported intrinsic motivation led to enhanced self-control performance on a second task, whereas those low in motivation showed a deterioration in antisaccade performance after initial self-control exertion (Kelly et al., 2015).

Increasing levels of self-awareness appears to have a similar restorative effect on temporary deficiencies in self-control following prior engagement. Focusing attention on the self can lead to the conscious awareness of the self, a state Duval, Wicklund, and Fine (1972) labeled "objective self-awareness." Moreover, it results in a process of self-evaluation, which consists of comparing the self to a standard of correctness that specifies a state the self ought to have (Duval et al., 1972). Specifically, anything that primes an individual about the self, such as mirrors, hearing one's own voice, or cameras, can increase self-awareness levels (Stapleton & Smith, 2013; Wicklund, 1979).

Indeed, it has been shown that self-focused attention has important implications for motivation and self-regulation (for reviews, see Carver, 2003; Duval & Silvia, 2001; Gibbons, 1990; Silvia & Duval, 2001). For example, previous research demonstrated a positive relationship between self-focused attention and self-control. Employing a sequential two-task depletion paradigm, Alberts, Martijn, and De Vries (2011) used a scrambled sentence task (SST) to induce self-awareness by priming participants with sentences connected to the self that began with the word "I." This was administered after the first self-control task—an auditory suppression task—and before a second self-control task, which measured perseverance level in a handgrip squeezing task. Those presented with neutral primes showed a temporary deterioration in self-control performance in the handgrip task and persevered for less time; however, inducing self-awareness counteracted this.

The finding that motivation and self-awareness moderate self-control performance support Beedie and Lane's (2012) resource allocation account. This posits that a temporary deficiency in self-control is reflective of a reluctance to allocate resources to a task because it is not a personal priority (i.e., considered important and/or interesting). Consequently, the response trajectory of a temporary deficiency in self-control performance following prior exertion reflects a person's low level of motivation, one unwilling to invest resources (Baumeister, 2014). Applying this to the self-awareness findings, making an individual more self-aware arguably might prompt them to improve their performance and motivate them to allocate resources to a second task despite initial exertion.

Alternative models also explain self-control performance deterioration from a motivational perspective (Inzlicht & Marcora, 2016). Baumeister's amendment to the original resource model suggested that resources are still somewhat diminished during self-control exertion but, if motivated, any remaining resources are allocated to the subsequent task (Baumeister, 2014; Inzlicht & Schmeichel, in press). The shifting priorities account (Inzlicht & Schmeichel, 2012; Inzlicht, Schmeichel, & Macrae, 2014) suggests that a motivational attentional shift produces the temporary reduction in self-control; one changes from completing a compulsory task to wanting to perform enjoyable tasks (Baumeister, 2014; Inzlicht, Legault, & Temper, 2014). The "opportunity cost" model suggests that the motivation for task completion stems from the opportunity cost associated with the task (i.e., perception of effort). Motivation is high when a task is perceived as less effortful (Kurzban, et al., 2013).

The current study aimed to further explore the motivational perspectives on self-control performance and assessed the relationship between self-awareness and motivation. We manipulated self-awareness by administering the SST task (Alberts et al., 2011) between two self-control tasks. Following our previous methodology (Kelly et al., 2015), an initial Stroop (incongruent vs. congruent) task was paired with an antisaccade task in a sequential two-task paradigm. The prosaccade task was also administered to assess whether completion of an initial self-control task adversely affected subsequent self-control performance only or whether the observed effects were extended more generically to other saccade tasks. Secondly, we measured self-reported levels of motivation using the intrinsic motivation inventory (IMI; McAuley, Duncan, & Tammen, 1989). Based on Alberts et al.'s (2011) findings, we hypothesized that heightening self-awareness levels would counteract the temporary deficiency in self-control performance in the antisaccade task following incongruent Stroop task completion. Further, drawing on our recent findings (Kelly et al., 2015), we predicted that high motivation would counteract such temporary decline and lead to sustained antisaccade performance. The relationship between the effects of self-awareness and motivation on self-control performance were examined to observe whether priming high self-awareness would be an intervention that would increase motivation and subsequently attenuate any self-control deficiency in performance.

Method

Participants

We initially tested 61 participants but removed one participant due to the high rate of erroneous responses made in the antisaccade task (89.29%), which indicated that the instructions were not fully understood. On average in the antisaccade task, the error rate for healthy participants is 20% (Hutton, 2008). This resulted in a final sample of 60 healthy young adults (12 male, 48 female) studying at Lancaster University (*M*age = 22.08 years). Before the commencement of the study, a power analysis based on Alberts et al.'s (2011) findings revealed that this sample size was sufficiently highly powered (0.74) according to Cohen's (1988) standards. This study was approved by Lancaster University's Ethics Committee, and written informed consent from all participants was provided according to the Declaration of Helsinki.

Procedure

Participants attended one testing session, which lasted on average 30 min. Participants were divided into four groups: incongruent Stroop/low self-awareness, incongruent Stroop/high self-awareness, congruent Stroop/low self-awareness, and congruent Stroop/high self-awareness. Participants first provided written informed consent and then completed either a congruent (control) or incongruent Stroop (which required self-control) task. The SST was then administered with participants instructed to unscramble 20 sentences to form grammatically coherent statements using five out of the six words available. Participants either received the version that primed self-awareness or a control (neutral/low self-awareness) version. Following this, the eye tracking equipment was set up, and participants completed the prosaccade and then antisaccade tasks. This was considered optimal due to evidence of carryover effects between the saccade tasks (Roberts, Hager, & Hare, 1994). After both saccade tasks, participants then completed the IMI, rating how meaningful/important they found the eye movement tasks to complete. At the end of testing, participants were fully debriefed.

Materials

SST. Participants were presented with a list of 20 scrambled sentences and instructed to unscramble each one to form a grammatically correct sentence. The self-awareness version of the task contained sentences, which when unscrambled began with "I" such as 'I read books for leisure," whereas the neutral (low self-awareness) task contained sentences, which when unscrambled started with different names such as "Catherine reads books for leisure."

IMI. Level of motivation was examined using the 36-item IMI. Participants made their responses on a 7-point-Likert scale, which varied from *not at all true* to *very true*. Example statements that required a response included "I thought this activity was quite enjoyable," "This activity was fun to do," "I felt like I had to do this," and "I think that this activity is useful to me." An indication of participants' overall level of motivation was provided by collating and averaging all 36 responses (Li, 2004).

Stroop task. This computerized task involved responding to the color (yellow, blue, green, purple, red) of a series of 135 words by pressing relevant keys on a QWERTY keyboard (based on the methodology used by Wallace & Baumeister, 2002). Participants engaged in either a congruent version (control) of the task, in which the ink color and the color words were identical or an incongruent version (depletion), in which they differed (e.g., the word purple was written in green ink). The incongruent task also required one to suppress this instruction when responding to the color *red* and alternatively responding to the written word. After the Stroop task, which was completed in 4 min 30 s, participants answered four questions, which examined different performance outcomes—pleasantness, level of effort exerted, frustration, and tiredness (see Denson, von Hippel, Kemp, & Teo, 2010)—in order to address whether there were differences depending on the two Stroop tasks that were completed.

Saccade tasks. Participants completed both a 30-trial prosaccade task (an eye movement is made toward a presented target) and a 30-trial antisaccade (Hallett, 1978) task (an automatic prosaccade toward the target is suppressed and an eye movement is directed to the opposite side, away from the target). Participants rested their head on a cushioned chin rest, which was located 57 cm away from a 19″ computer, and the saccade tasks were presented on the screen. An Eyelink 1000 (SR Research: 1,000 Hz, $< .5°$ accuracy) recorded saccadic responses. During both tasks, a fixation cross appeared in the middle of the screen and after an interval of 1,000 ms, the target—a small green dot (.6° diameter)—appeared 8° either to the left or right of the fixation cross. The target and fixation cross both stayed on the screen for 1,000 ms (overlap), and a 1,500-ms interval preceded the next trial. Target location was randomized and appeared to the left or right of the screen with equal frequency. Calibration and validation procedures before each task were completed, which ensured all recordings were of a good and consistent standard.

Analysis

All statistical analysis was performed in R (R Core Team, 2015) using the linear mixed effects model package; lme4 (Bates, Maechler, Bolker, & Walker, 2014). For this analysis, as participants completed a series of trials, we included a random effect for participant, to account for individual variation (Winter, 2013). A 2 (Self-Control condition: self-control/depletion vs. control) $\times$ 2 (Self-Awareness manipulation: high vs. low/neutral) $\times$ 2 (Saccade Task: prosaccade and antisaccade) mixed factorial design with repeated measures on the third factor (saccade task) was conducted. We measured saccade performance in the eye movement tasks based on two specific parameters: saccade latency (response speed) for correct responses and the rate of erroneous responses (for the antisaccade task only). Saccade response speed was calculated using the period between the target onset and the start of the first saccade, with amplitudes of 2° degrees or more. Responses of less than 80 ms and over 500 ms were classified as anticipatory or late saccades, respectively, and removed from the analysis. For the number of errors committed in the antisaccade task, the total number of errors (incorrect saccades made toward rather than away from the target) was obtained relative to the number of correct saccadic responses directed away from the target.

Response speed (latency). We performed a linear mixed effects analysis to examine whether self-control condition, self-awareness manipulation, and/or motivation influenced saccadic response speed. Initially, we fitted a null model, which included participant as a random effect. We only had one item (green dot) and thus did not include item as a random effect. We then ran through a series of models, adding task type (prosaccade and antisaccade), self-control condition (depletion vs. control), and self-awareness (high vs. neutral/control) as fixed effects, along with motivation as a covariate. We compared models with fixed effects and also those with interactions between the fixed effects using the likelihood ratio test.

Correct versus erroneous antisaccade responses. For correct compared to erroneous antisaccade responses, we performed a generalized linear mixed effects analysis. Specifically, we ran through a series of separate models treating participants as random effects and both self-control condition (depletion vs. control) and self-awareness condition (high vs. low/neutral) as fixed effects. Self-reported motivation was then added as a covariate to the models to assess whether differences in motivation significantly predicted the rate of errors compared to correct antisaccade responses.

Results

Self-Reported Performance Differences Based on the Initial Task Completed (Manipulation Check)

We conducted general linear modeling analysis to assess whether self-reported ratings of task pleasantness, tiredness, frustration, and effort expended differed significantly depending on the initial Stroop task (congruent/control vs. incongruent/depletion) completed. This revealed no significant differences in task pleasantness,

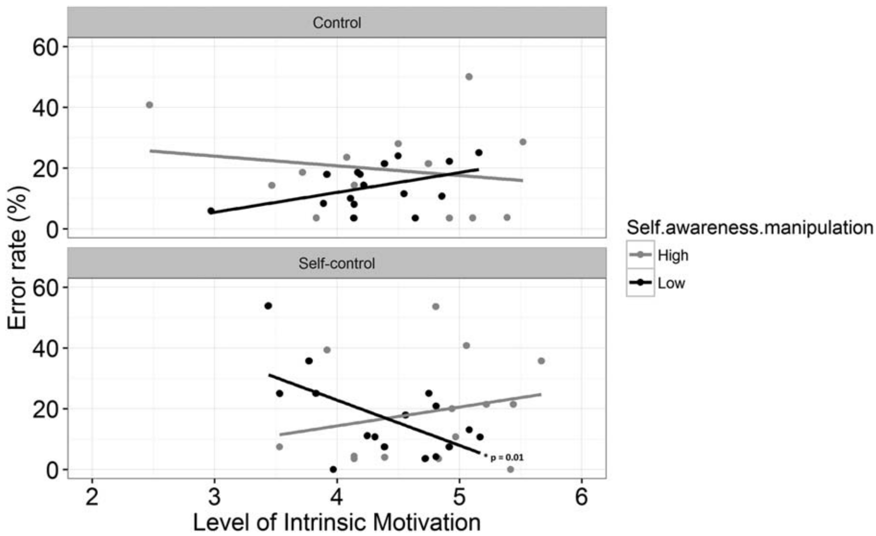

Figure 1. The relationship between motivation, self-awareness manipulation, and self-control condition for the proportion of erroneous antisaccade responses.

$F(1,58) = 0.20$, $p = .66$, or ratings of tiredness, $F(1,58) = 1.98 \times 10^{-29}$, $p = 1.00$, between the two versions. However, there was a significant effect of frustration, $F(1,58) = 10.72$, $p < .001$; the incongruent (vs. congruent) Stroop task was reported to be more frustrating to complete, $\beta = -1.40$, $SE = 0.43$, $t = -3.28$, $p < .001$, than the congruent Stroop task. There was also a significant effect of effort, $F(1,58) = 30.44$, $p < .001$; the congruent was rated as requiring less effort than the incongruent Stroop task, $\beta = -2.20$, $SE = 0.40$, $t = -5.52$, $p < .001$.

Accuracy. The incongruent version of the Stroop task, which required self-control, was performed with less accuracy ($M = 89.57$, $SD = 11.88$) than the congruent (control) version ($M = 99.71$, $SD = .55$); specifically those completing the congruent version performed with on average 13.14% greater accuracy, $\beta = 13.14$, $SE = 2.17$, $t = 6.05$, $p < .001$.

Saccade Performance

Response speed (latency). Comparing the null model to a model that also included task as a fixed effect revealed task to be a significant predictor of saccade response speed, $\chi(1)^2 = 999.78$, $p < .001$; the prosaccade task was performed 60.48 ms ± 1.77 (*SE*s) faster than the antisaccade task. Adding self-control condition as a fixed effect to the model did not improve the model fit, nor did including self-awareness condition and motivation and their interactions ($p > .05$). Results showed that participants were faster to perform the prosaccade compared to antisaccade task. The effects of self-control condition and self-awareness were not significant. Further, self-reported levels of motivation did not significantly predict response speed in either task.

Correct versus erroneous antisaccade responses. Firstly, fitting a model with self-control condition (depletion vs. control) as a fixed effect and participants as random effects showed self-control condition to be not a significant predictor of correct antisaccade responses; those that engaged in the initial depletion (incongruent Stroop) task ($M = 17.91$, $SD = 15.25$) committed a similar rate of errors to those that completed the control (congruent Stroop) task ($M = 18.03$, $SD = 14.19$) $\beta = -0.07$, $SE = 0.28$, $Z = -0.24$, $p = .81$. Secondly, we added self-awareness to the model, which revealed this to be not a significant predictor of responses; those primed with self-awareness ($M = 19.24$, $SD = 15.78$) produced a comparative rate of errors to those primed with neutral words ($M = 16.92$, $SD = 13.73$) $\beta = 0.17$, $SE = 0.39$, $Z = -0.43$, $p = .67$. There was also no significant Self-Awareness × Initial Condition interaction ($p = .74$). Adding self-reported levels of motivation produced no significant effect of motivation, $\beta = 0.03$, $SE = 0.50$, $Z = 0.07$, $p = .95$, nor was there a significant Initial Condition × Motivation interaction ($p = .14$).

However, a significant three-way Self-Control × Self-Awareness × Motivation interaction on rate of erroneous responses (see Figure 1) was observed, $\beta = 1.86$, $SE = 0.88$, $Z = 2.11$, $p = .03$. Examining this interaction further and splitting by self-control condition, for participants that completed the incongruent Stroop task (self-control task), a negative relationship between erroneous responses and motivation was observed, $\beta = -0.96$, $SE = 0.\ 48$, $Z = -1.99$, $p = .04$, indicating that when motivation was high, fewer erroneous responses were made in the antisaccade task. Although self-awareness alone did not predict erroneous responses in the antisaccade task ($p > .05$), there was a significant Motivation × Self-Awareness interaction, $\beta = 1.58$, $SE = 0.68$, $Z = 2.34$, $p = .02$. Those that had previously applied self-control (in the incongruent Stroop task) and received the self-awareness primes performed a similar rate of antisaccade errors regardless of their level of motivation to complete the antisaccade task, $\beta = 0.66$, $SE = 0.58$, $Z = 1.13$, $p = .26$. For participants that completed the incongruent Stroop task and were not self-primed, level of motivation predicted erroneous relative to correct antisaccade responses; those high in motivation produced fewer erroneous responses than those low in motivation, $\beta = -0.98$, $SE = 0.37$, $Z = -2.77$, $p = .01$ (see Figure 1). These findings were not extended to the control group (i.e., those participants that first completed the congruent Stroop task).

Discussion

The current study explored whether the temporary deficiency in performance that is typically observed in the second of two sequential self-control tasks can be overcome by high motivation and increased self-awareness. According to the resource depletion theory (Baumeister et al., 2007), the reduction in performance consistently noted in a second of two sequential self-control tasks stems from self-control being an effortful process that relies on the availability of a limited energy resource, which reduces through exertion. Based on a previous methodological design (e.g., Kelly et al., 2015), we administered either a congruent (control) or incongruent Stroop task to participants followed by the prosaccade and antisaccade eye movement tasks. However, before the saccade tasks, we manipulated self-awareness by administering a SST. Self-reported levels of motivation were also measured using the IMI after the saccade tasks were completed.

The findings revealed that performing an initial self-control task per se did not predict subsequent self-control performance. The current data suggest a complex relationship between self-control exertion, priming of self-awareness, and level of motivation for correct, compared to erroneous, antisaccade responses. Level of motivation only predicted antisaccade performance when participants were not primed on self-awareness; those low in motivation committed more erroneous responses than those high in motivation. Thus, only participants with low motivation to perform the second self-control task showed the typical self-control depletion effect consistent with the self-control literature (Hagger et al., 2010), that is, a temporary deficiency in self-control ability in the second task following prior exertion. When participants were primed on self-awareness, motivation did not predict subsequent self-control performance. This opens up the possibility that priming self-awareness led to an increase in motivation, which in turn counteracted any temporary deficiency in self-control. These findings are in line with previous research that demonstrated (a) differences in subsequent self-control performance following the initial exertion of self-control based on motivation, and (b) no difference in self-control performance for individuals who were exposed to an explicit manipulation of motivation (Alberts et al., 2011; Kelly et al., 2015; Muraven & Slessarva, 2003). According to Wicklund (1979), raising self-awareness increases motivation, as the individual is made aware of their performance level, which subsequently increases the motivation to perform a task well.

The findings suggest that an individual who is motivated to complete a task—either through manipulation of self-awareness or intrinsic high levels of motivation—will successfully engage in a subsequent task of self-control despite earlier self-control exertion. This supports growing evidence that one's level of motivation rather than limited resource capacity influences changes in self-control performance over time (Molden, 2013).

Although the findings are consistent with a motivational account of self-control, the question arises to what extent motivational factors can compensate for limited resources (Alberts et al., 2011). According to the resource allocation theory (Beedie & Lane, 2012), resources (i.e., glucose) will be assigned based on one's intrinsic level of motivation to complete that task. However, it is as yet unclear which underlying mechanisms determine this allocation of additional energy resources. Specifically, understanding the neurochemical mechanisms behind these findings is needed (Legault & Inzlicht, 2013).

High levels of motivation could trigger an arousal/activation response resulting in energy in the form of glucose to be directed to specific brain areas for successful task completion. Specifically, being motivated to perform a task may have led to activation of the sympathetic adrenal medulla axis, which results in the release of adrenaline (epinephrine) from the adrenal medulla and leads to increase in blood glucose levels. This is in line with recent research, which showed that increasing motivation led to an increase and/or maintenance of blood glucose levels associated with maintenance of performance levels during the second self-control task. This suggests that being motivated allows allocation of energetic resources to a task, which in turn prevents performance decrements (Kazén, Kuhl, & Leicht, 2015).

Another potential underlying mechanism that might mediate maintenance of performance levels is dynamic change in dopamine activity. Dopamine activity has been associated with a number of psychological processes including motivation. Potts, Martin, Burton, and Montague (2006) have suggested that allocation of resources to limited-capacity systems might be regulated by dopaminergic reward system input. In the current context, increased dopaminergic activity could be linked with high motivation and the subsequent allocation of energetic and/or cognitive resources to a task. This is supported by recent conceptualizations of dopamine, which suggest the involvement of dopamine beyond solely reward processing (Salamone & Correa, 2012). In particular, the role of dopamine in the nucleus accumbens is considered to be more wide ranging and linked to the engagement of effort and decision making (Salamone et al., 2007).

More specifically, it has been argued that dopamine controls the amount of energy one expends in achieving a goal, particularly when it is considered valuable and important (Salamone et al., 2007). When dopamine levels are higher, one is more engaged in an activity and injects more resources into its completion (Beeler, Frazier, & Zhuang, 2012). For example, Treadway et al. (2012) observed that lower levels of dopamine led one to favor less effortful tasks, whereas enhanced dopamine levels made one willing to expend effort for a reward. In addition, an inverted U-shaped relationship has been observed between dopamine level and sequential self-control performance (Dang, Xiao, Liu, Jiang, & Mao, 2016). Participants with "medium" dopamine levels—as measured by eye-blink rate, which is considered a valid measure of dopamine levels (Karson, 1983)—performed well, that is, less erroneously in a second task of self-control (the antisaccade task) despite initial exertion in a Stroop task compared to those with higher or lower levels.

However, more research is needed to elucidate the role of dopaminergic systems in the complex relationship between self-control, motivation, and resource allocation,

Consequently, based on the existing evidence, the findings support Beedie and Lane's (2012) resource allocation account that being motivated resulted in resources being allocated to task. Although Baumeister's (2014) amended resource theory accounts for the moderating effect of motivation, it still posits that resources are depleted following self-control exertion, and as more recent research findings have failed to observe this (Kelly et al., 2015; Molden et al., 2012; Sanders et al., 2012), an account of targeted resource allocation (Beedie & Lane, 2012) seems more appropriate. It is difficult to refute a resource perspective fully, specifically given the evidence on the resource accounts and also given that glucose is an essential energy resource for the brain and vital for cognition. Thus, it seems plausible that glucose is required for self-control, albeit other factors are likely to moderate this relationship.

Interestingly in the current study, performance differences were only observed for correct compared to erroneous responses and not for response speed in the antisaccade task. As expected, prosaccade responses were significantly faster than antisaccade responses; however, neither self-awareness nor motivation directly influenced response speed. This replicates our previous study (Kelly et al., 2015), which only observed performance differences based on motivation level for errors performed. This implies a more direct motivational effect for erroneous compared to correct antisaccade responses, which were not influenced by the effects on response speed. As a result, the evidence more strongly supports the observation that being highly motivated counteracts the effects of self-control deficiency following prior exertion.

Although we replicated Alberts et al.'s (2011) design with the implementation of a SST to induce self-awareness, it would be interesting if further research expanded these methods by directly manipulating self-awareness possibly with a mirror, for example, to further assess the link between self-awareness and self-control. Moreover, it would also be beneficial to build on the findings of the relationship between self-reported motivation and self-control by further manipulating levels of motivation to assess in more detail whether motivation has an ameliorating effect on self-control deficiency in a similar way.

Conclusions

This study investigated the effect of self-awareness and motivation on self-control performance over time and observed whether a temporary deficiency in performance in the second task following prior exertion could be restored. The findings revealed that, following the exertion of self-control, self-reported levels of motivation significantly predicted the rate of erroneous responses for those not exposed to the self-awareness primes. When self-awareness was induced, there were no differences in antisaccade responses based on motivation level. This arguably supports a motivation resource account; following the application of self-control, if one is motivated to perform a second self-control task—stemming from self-awareness resulting in one wanting to perform well or, if this is not induced, based on how interesting and/or enjoyable the task or tasks were perceived to be—this has a restorative effect on a temporary deficiency in self-control ability, leading one to allocate resources and perform the second task well. This supports the idea of self-control performance based on more targeted allocation of resources rather than depletion and shows that interventions targeted at motivation can help overcome the effect of impaired self-control performance following prior exertion.

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Paper six: Sequential self-control task performance: the role of both motivation and age.

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Abstract

Self-control, which involves behavioural regulation, is part of the executive control system, pertaining to dorso-lateral-prefrontal-cortex function. Although important and regularly used, self-control is effortful and performance wanes over time. Completing two sequential self-control tasks, the first is performed well but performance typically deteriorates in the second. The resource depletion theory argued this stemmed from self-control relying on the availability of a limited energy resource, which reduces through self-control exertion. Addressing a research gap, the effect of age on self-control performance across two sequential self-control tasks - an attention video task and an incongruent Stroop task - was examined; previous research primarily relied on younger aged samples and research with older aged adults was lacking. Consequently, participants' aged 18 to 80 years were recruited. Additionally, any motivation effects on self-control performance were examined, to observe whether high levels of intrinsic motivation had a restorative effect on any temporary impairment in self-control following prior exertion. Findings showed that applying self-control in the video task, led to older than younger aged adults performing the subsequent Stroop task more slowly; with this being somewhat counteracted for those high in motivation. Findings suggested that age related decline in self-control ability and concomitant behavioural constructs such as willpower could be overcome through motivational mechanisms. Self-control can be exerted but due to age related decline in high level cognition, intrinsic motivation needs to be greater to ensure continual successful self-control performance.

Key words: self-control, age, motivation

Sequential self-control task performance: the role of both motivation and age

Cognitive control is a vital part of cognition, linked to the top down processing of information and executive control, involving executive functions (EFs) of the frontal brain regions: inhibition/self-control, working memory and mental flexibility (Diamond, 2013; Manard, Carabin, Jaspar, & Collette, 2014). Evidence suggested that within tasks that demand such cognitive control and attentional resources, an age-related decline may occur (Manard et al., 2014).

In the current study we examined the relationship between age and performance in tasks pertaining to one particular executive function that requires cognitive control, namely self-control/inhibition; i.e. the intentional act of overriding a dominant/habitual response for another. Previous research has shown an age-related performance decline on self-control tasks (von Hippel, Silver & Lynch, 2000). For example, employing the incongruent Stroop task as a measure of self-control (where one must inhibit the automatic response of reading the word and respond to the words' colour), older aged adults performed slower and made more errors compared to younger aged adults (Baena, Allen, Kaut & Hall, 2010).

The effects of performing two consecutive self-control tasks have been widely studied in younger aged populations and evidence consistently shows that when completing two sequential self-control tasks, the first task is performed well but a temporary impairment is observed in the second (Baumeister, Vohs & Tice, 2007; Hagger, Wood, Stiff & Chatzisarantis, 2010). Indeed, over eighty studies have supported this observation (see meta-analysis by Hagger et al., 2010). The strength model/resource depletion theory of self-control (Baumeister et al., 2007; Baumeister, 2014) argued that this deterioration stems from a reduction in the availability of an energy resource – glucose (Gailliot et al., 2007) – that fuels self-control. Self-control exertion temporarily reduces this resource, resulting in limited resource availability for subsequent self-control performance.

However, sequential self-control performance has predominantly been examined in younger participants, aged 18 to 25 years (Hagger, et al., 2010; Dahm, Neshat-Doost, Golden, Horn, Hagger & Dalgleish, 2011) and the few studies that examined sequential self-control task performance in older aged samples observed mixed findings (e.g. Dahm et al., 2011, Bray, Ginis & Woodgate, 2011; Boyle, Lawton, Allen, Croden, Smith & Dye, 2016). Dahm et al. (2011) compared performance of an autobiographical memory task in younger (18-25 years) and older (40-65 years) participants after Stroop task (incongruent or congruent) completion. Although Dahm et al (2011) did not employ two measures of self-control it was insightful as it showed that a temporarily reduction in performance in a second task following prior exertion does not extend to older aged adults; only younger aged adults recalled fewer accurate memories. However, Dahm et al.'s (2011) older aged group had a maximum age of 60 years; a larger age range could have provided more insight into the relationship between age and self-control performance. And employing age as a continuous variable may have provided more sensitive analyses rather than as a two level factor (Cohen, 1983).

Bray et al. (2011) examined sequential self-control performance in participants with an average age of 71 years, using two frequently used tasks (Hagger et al., 2010); an incongruent Stroop task (Wallace & Baumeister, 2002) followed by a hand-grip task, where persistence was used as a measure of self-control. Findings showed that following self-control exertion in the Stroop task, older aged participants persisted for less time in the hand grip task. This was consistent with previous findings with younger aged participants (Hagger et al, 2010). However, Xu et al. (2014) found no evidence for a temporary impairment in self-control performance in a second task in both young (19.7-21.2) and middle aged (41.6-43.6) participants despite employing frequently used self-control tasks (erasing letters, Stroop and handgrip tasks). Further, Scheibe and Blanchard-Fields (2009) observed that being tasked with having to regulate emotions while watching a video, appeared to be less costly and thus less depleting for older than younger adults, suggesting differences across the lifespan in vulnerability to the costly nature of regulating emotions.

The studies discussed above are the few, which have assessed potential age related differences in sequential self-control performance and their results are equivocal. The current study aimed to further explore any age related differences in sequential self-control task performance by recruiting a wider age pool of participants aged between 18 and 80 years.

Although the observation that self-control ability temporarily wanes with continued exertion was previously reported as robust (Hagger et al., 2010), a number of studies have failed to replicate these findings irrespective of sample age (Carter, Kofler, Forster, & McCullough, 2015; Hagger et al., 2016; Wang & Huangfu, 2016), and thus refuted the previous evidence. Consequently, to address the issue surrounding replication in the self-control literature, we employed two commonly used self-control measures from the literature (Hagger et al., 2010; Carter & McCullough, 2014; Carter et al., 2015); an attention video task paired with an incongruent Stroop task (Gailliot et al., 2007; Molden et al., 2012).

In addition, we explored the role of motivation on self-control performance. Motivation has previously been observed to have a moderating effect on one's ability to apply self-control continually over time; high motivation predicted successful self-control performance (Muraven & Slessareva, 2003). Specifically, low levels of self-reported intrinsic motivation have been associated with performing more erroneously in a subsequent self-control task, whereas high motivation counteracted any self-control deterioration (Kelly et al., 2015). Indeed, more recent theories posit that motivation plays a key role in self-control performance. The resource allocation account (Beedie & Lane, 2012) suggests that motivation to complete a task, based on its inherent interest or how personally meaningful it is, results in the allocation of resources irrespective of initial exertion. If, however, motivation is low, resources will not be allocated and a temporary impairment in performance occurs. Further, the shifting priorities account (Inzlicht & Schmeichel, 2012) which takes a non-resource perspective, states that a temporary deficiency in self-control ability stems solely from a decline in attention and motivation; following acts of self-control people become less motivated to engage in another act of self-control and become more motivated to engage in tasks that are personally rewarding and enjoyable which in turn leads to performance deterioration in the second tasks which requires self-control. However, if motivation to perform the second self-control task is high then no such depletion occurs. Drawing on these theories the current study examined whether high intrinsic motivation counteracts a temporary deficiency in self-control performance.

There are reported age related differences however in the type of motivation that is valued and this has been demonstrated specifically in the literature with motivation in the work place. In particular Inceoglu, Segers and Bartram's (2012) research demonstrated that with increasing age, one was more motivated intrinsically such as valuing the autonomy and choice over performing work tasks rather than being motivated extrinsically by monetary rewards. There was thus not a decline in motivation but an alteration in what older aged people were motivated by. In fact a meta-analysis by Kooij, Lange, Jansen, Kanfer and Dikkers (2011) revealed that intrinsic motives were more important with increasing age than extrinsic motives such as rewards. It arguably would be interesting to examine if older aged participants in this sample were motivated more intrinsically than the younger sample and how this relates to sequential self-control task performance.

In summary, the current study examined sequential self-control performance – using two measures of self-control (attention control video task and Stroop task) that have been frequently used in previous studies on sequential self-control task performance (Hagger et al., 2010) - across a wider age range of participants to observe whether a temporary deterioration in self-control could be found across the lifespan. The moderating effects of intrinsic motivation on self-control were also explored along with the relationship between age and motivation on self-control performance. Given the lack of research exploring the relationship between age and self-control performance and the mixed results, we predicted that age would moderate self-control performance but not its direction. Further, based on previous evidence (e.g. Muraven & Slessareva (2003) we expected intrinsic motivation to modulate self-control performance in the subsequent task following prior exertion. The examination of any age by initial condition by intrinsic motivation interaction was exploratory given the lack of evidence on this.

Method

Design

The study employed a one way (initial condition; self-control task vs. control task) between-subjects design.

Participants

Eighty-six (60 females, 26 males) healthy adult volunteers aged between 18 and 80 years (M = 36.20, SD = 20.16) were recruited from Lancaster University (students obtaining course credit) and the Lancaster area (via the local library in Lancaster and three community engagement days in Lancaster city centre called ‘Campus in the City’). The data of six participants had to be removed from the data set as the Stroop task was not fully completed, leaving a final sample of 80 participants (57 females, 23 males) with a mean age of 34.80 years (SD = 18.90; see figure 1 for the age distribution of the sample). Participants were randomly assigned to the experimental condition; either the initial self-control task or control task. Ethics approval was granted by Lancaster University’s Ethics Committee and participants gave written informed consent in line with the Declaration of Helsinki.

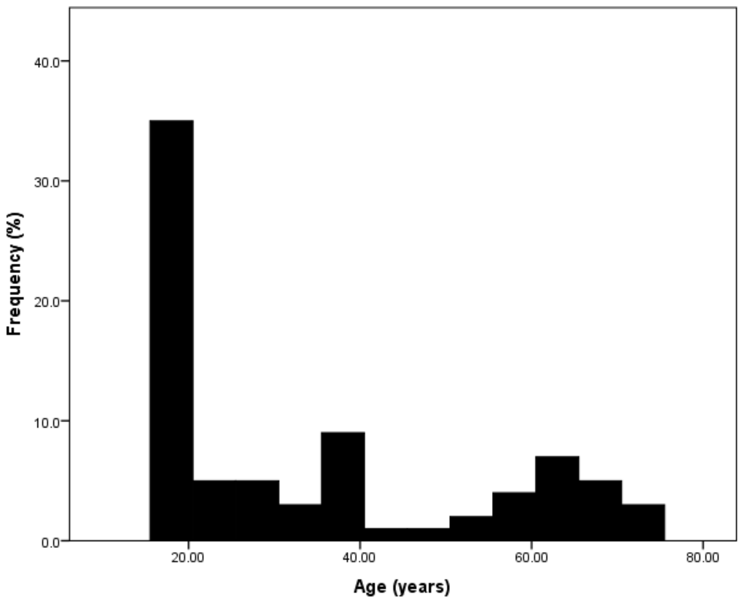

Figure 1: Age distribution of the sample

Materials

Initial depletion task: A six minute 30 second attention control video (without sound) was presented on a laptop computer screen to participants. On the left hand side, a female speaking was presented and on the right hand side words (e.g. floor, cut, horn) were presented sequentially every 10 seconds. For the control task, participants were instructed to watch the video as they would normally a television programme. In the self-control condition, participants were instructed to focus their attention solely on the female speaking and ignore the words that were presented on the right hand side. Taken from Graham and Bray (2012) a series of four questions were administered after the completion of the video task to assess level of tiredness, effort exerted, and how pleasant and frustrating the task was perceived to be. This assessed whether there were differences in self-reported ratings between the two groups that were or were not instructed to exert self-control in the video task.

Dependent measure of self-control: A 135 trial incongruent Stroop task (Stroop, 1935) was presented in which a sequential list of colour words appeared on the screen and participants were instructed to respond to the ink colour of the word (yellow, green, blue, purple or red) as quickly as possible by pressing particular keys on a keyboard. All words presented were written in an incongruent colour to the actual word i.e. the word blue was written in green ink.

Intrinsic Motivation Inventory [McAuley, Duncan & Tammen, 1989, Ryan, 1982]

To assess how intrinsically motivated participants were the intrinsic motivation inventory (IMI) was administered. Participants responded to a series of 36 questions which included, ‘I enjoyed doing this activity very much’, ‘This activity was fun to do’, ‘I did this activity because I wanted to’ and ‘I would be willing to do this again because it has some value to me’. Responses ranged from ‘not at all true’ to ‘very true’ on a 7 point Likert scale. The answers were collated to give an average intrinsic motivation score (McAuley, Duncan & Tammen, 1989, Ryan, 1982; Li, 2004).

Procedure

Participants entered the laboratory and provided written informed consent. Then based on the sequential two task paradigm, they engaged in an attention control video task that either required self-control or did not (initial condition; self-control vs. control). Participants were then asked how frustrating or pleasant they found the task along with how much effort they felt they expended and how tired they felt after task completion (manipulation check). Participants then completed the incongruent Stroop task (Stroop, 1935). After Stroop task completion, the IMI was administered – in which responses were based on the completed Stroop task - and participants answered some demographic questions (age, gender). At study conclusion, participants were thanked and fully debriefed.

Results

Statistical analysis

Two performance parameters were measured during the completion of the incongruent Stroop task; reaction time (RT) for correct responses and percentage error rate (%). Using IBM SPSS Statistics version 20, both performance parameters were analysed using linear mixed effects modelling (F values were drawn from '*Type III Tests of Fixed Effects*'). We ran through a series of models including participant as a random effect (to account for individual variation across the 135 trials of the Stroop task; Winter, 2013), adding initial task completed (self-control versus control) as a fixed effect. Self-reported level of motivation and age were both added as covariates to the models.

Attention control video task manipulation check

Using linear modelling, we assessed whether the version of the video task that required self-control differed to the control version in terms of self-reported levels of effort and tiredness following task completion and also how pleasant and frustrating the task was perceived to be. The level of effort expended significantly differed between the two tasks [β = .99, SE = .38, t (80) = 2.64, p = .01]; participants reported to apply more effort in the self-control version of the video task (M = 4.09, SD = 1.73) than in the control version (M = 3.10, SD = 1.68). Although the effect of task on reported levels of tiredness failed to reach significance [*B* = .65, SE = .35, t (80) = 1.84, p = .07], inspection of the means revealed higher levels of tiredness following exertion of self-control (M=3.41, SD = 1.52) compared to the control condition (M = 2.77, SD = 1.66). Additionally, exerting self-control in the video task was reported to be more frustrating (M = 3.46, SD = 1.76) than merely watching the video (M = 2.74, SD = 1.77) with this approaching significance [*B* = .72, SE = .39, t (80) = 1.84, p = .07]. There were no differences in ratings of task pleasantness between the two initial task conditions [*B* = - .08, SE = .27, t (80) = -.27, p = .79]; the self-control task (M = 3.98, SD = 1.21) was reported equally as pleasant to complete as the control task (M = 4.05, SD = 1.30).

Stroop task performance

Stroop RT for correct responses*:* A model was initially fitted with participant as a random effect and initial task as a fixed effect. For initial task completed [F (1, 80) = 2.08, p = .15] inspection of the means illustrated that those applying self-control in the first task responded 14.17 slower (see Figure 2) in the subsequent Stroop task than those that completed the control task [*B* = 14.17, SE = 9.84, t (80) = 1.44, p = .15].Adding age as a covariate showed this to significantly predict response speed [F (1, 80) = 109.47, p = .000]; as age increased, response speed got slower [*B* = 1.23, SE = .25, t (80) = 4.88, p = .000]. The age by initial task interaction was also significant [F (1, 80) = 8.78, p = .004]. Exploring this interaction further showed that in both the self-control [*B* = 2.21, SE = .21, t (41) = 10.73, p = .000] and control [*B* = 1.23, SE = .26, t (39) = 4.77, p = .000] groups, age significantly predicted performance; with increasing age, response speed slowed in the Stroop task. When motivation was added as a covariate to the model the effect of age [F (1, 80) = 3.20, p = .08] and the age x initial condition interaction [F (1, 80) = 1.86, p = .17] just failed to reach significance. No significant three-way interaction between initial condition, age and motivation [F (1, 80) = 1.14, p = .28] was observed. However, after examining the results by condition (i.e. initial task completed), clear differences were observed between the groups. When controlling for motivation then for those in the self-control group, age was a significant predictor of response time [F (1, 41) = 8.34, p = .006]; for every increase in age, there was a slowing in response speed [*B* = 5.11, SE = 1.77, t (41) = 2.89, p = .006], which was not extended to the control group [p > .70]. The age by motivation interaction failed to reach significance [*B* = - .622, SE = .38, t (41) = -1.65, p = .11] but suggested that the effect of motivation on response speed changed depending on the age of the participant. Specifically, with increasing age, level of motivation had a greater influence on response speed; motivation level moderated response time more for older than younger aged participants.

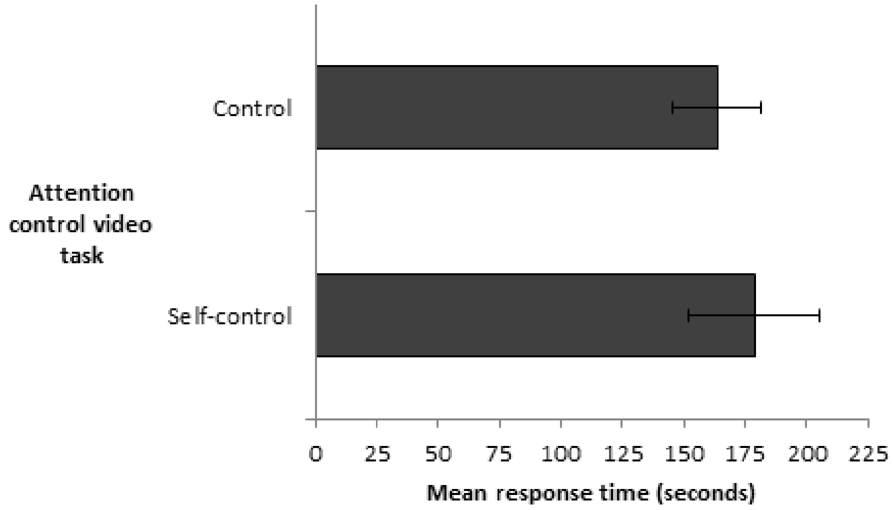

Figure 2: Stroop response time (seconds) for correct responses based on the initial task completed.

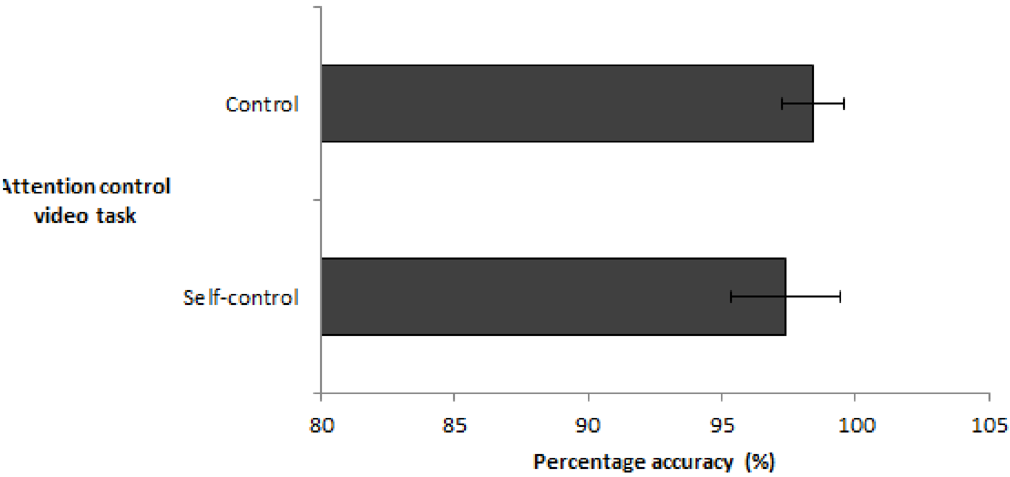

Figure 3: Stroop performance accuracy (%) based on the initial task completed.

Performance accuracy in the Incongruent Stroop task*:* Initially fitting a null model with participant as a random effect and initial task completed revealed initial task to not be a significant predictor of error rate [F (1, 80) = 1.82, p = .18]. There was no significant difference in the level of accuracy between the two initial task conditions [*B* = - .99, SE = .74, t (80) = - 1.35, p = .18] but inspection of the means showed that accuracy was lower after exerting self-control in the initial task (M = 97.41, SD = 4.10) than completing the control version of the task (M = 98.41, SD = 2.28) (see Figure 3). Adding age as a covariate revealed this to not be a significant predictor of erroneous responses [F (1, 80) = .02, p = .89] and the initial task x age interaction failed to reach significance [F (1, 80) = 3.47, p = .07]. Moreover, adding motivation as a covariate to the model revealed no significant main or interaction effects (p > .05).

Discussion

In healthy aging, tasks pertaining to cognitive control processes such as EFs observably suffer from age related decline (Manard et al., 2014; Braver & Barch, 2002). The current study investigated one aspect of cognitive control – self-control – and any age effects on self-control performance, in the sequential completion of two tasks. This extended the previous literature as research had predominantly relied on younger aged participants (Dahm et al., 2011). Noting the existing issue about replication (Carter et al., 2015), the current study also employed two regularly used self-control tasks (Hagger et al., 2010); an attention control video task and an incongruent Stroop task (Stroop, 1935). Further, the potential modulating effects of intrinsic motivation on sequential self-control task performance were explored.

The data revealed that applying self-control in the video task (ignoring the words), compared to completing the control task (watching the video) required more effort, and was perceived as more tiring and more frustrating to complete. Further, exerting self-control led to participants responding more slowly in the subsequent Stroop task than those that did not apply self-control in the initial task (i.e. just watched the video) though this was not significant. This observation therefore only tentatively supports the response trajectory typically outlined by the resource depletion theory (Baumeister et al., 2007); applying self-control in an initial task produced a temporary deterioration in one's ability to apply self-control in a subsequent task.

This performance decrement– in terms of a slower response - in the second of two concurrent self-control tasks was observed for younger and older aged participants. Consequently, previous findings were replicated and extended across the life span. Age predicted response speed and this was more strongly observed after self-control was initially applied in the attention control video task; older as opposed to younger aged participants made slower Stroop responses. Thus exerting self-control in an earlier task negatively affected self-control ability in a subsequent task more strongly for older than younger aged participants. This is consistent with previous evidence which showed that younger aged adults performed self-control tasks better than older aged adults (von Hippel, et al., 2000). The current findings are also supportive of the ageing literature in general as it is often observed that detriments occur in speeded tasks rather than accuracy, i.e. younger and older aged adults perform tasks at a similar level of accuracy, but older aged adults tend to make slower responses (Ratcliff, Thapar & McKoon, 2010). This might also account for why any performance differences were only observed for speed of response and not for accuracy.

In terms of the role of motivation, there was no significant three way interaction between initial condition, age and intrinsic motivation. However for participants that initially applied self-control in the first task and completed two sequential self-control tasks, motivation was observed to more strongly predict-response time for older than younger aged participants. Specifically, the more motivated older aged participants were the quicker their response speed in the Stroop task; those low in motivation were slower to make the appropriate Stroop response. Thus motivation moderated self-control performance across two self-control tasks but greater effects were observed as the age of the participant increased.

This interpretation of the evidence however is more preliminary – due to lack of a three way interaction between age motivation and initial condition - the data arguably tentatively suggests that when completing two sequential self-control tasks, resources were allocated (Beedie & Lane, 2012) to the second task when levels of intrinsic motivation were high and more so with increasing age. One could speculate that the reason why motivation appeared to be more influential for successful performance in older adults stems from metabolic and or/cognitive resources being more limited with increasing age and therefore cognitive tasks are costlier. Indeed, the rate of glucose brain metabolism changes across the life span with a significant age-related decline in cerebral glucose metabolism (Chugani, 1998; Moeller et al., 1996). For example, the cerebral blood flow particularly in the frontal regions of the brain, namely the prefrontal cortex decreases with age (Martin, Friston, Colebatch, Frackowiak,1991) and specifically in the areas that are involved in high level cognitive performance (Peters & Jones, 2013; Tisserand & Jolles, 2003).

Consequently, the observed protection of cognitive ability by high levels of motivation does offer support to theories which argue for motivation as a moderating (Beedie and Lane, 2012) or mediating factor (Inzlicht & Schmeichel, 2012) in self-control performance. More specifically, high levels of intrinsic motivation might have led to the allocation of resources to the second task despite initial self-control exertion (resource allocation account; Beedie and Lane, 2012) or high motivation *per se* boosted performance by sustaining and monitoring attentional resources (non-resource shifting priorities account; Inzlicht & Schmeichel, 2012; Inzlicht & Schmeichel, 2016).

Implications

Filling a research gap, we directly explored the relationship between age and motivation on sequential self-control performance over time. The findings tentatively suggest that age related decline in self-control ability can be overcome through motivational mechanisms, however we consider this to be more preliminary evidence, which requires further exploration. This is important as in healthy aging, cognitive control processes decline and a way of improving this would be beneficial, particularly as they are important for daily functioning (Manard et al., 2014). The current findings therefore might suggest that altering levels of intrinsic motivation might be a possible way to improve cognitive control impairments. Lifestyle and health-related factors represent an important category of risk factors for cognitive aging with evidence suggesting that positive changes in health behaviour can decrease prevalence of dementia (Bishop, Lu & Yankner, 2010; Kapogiannis & Mattson, 2011; Matthews et al., 2013). The rise in obesity, diabetes and metabolic syndrome in recent years highlights the need for targeted dietary and lifestyle strategies to promote healthy lifestyle and brain function across the lifespan. Lifestyle changes are difficult to execute and to maintain, but present an exciting potential for optimizing cognitive performance across the lifespan. The data of the current study provides promising initial evidence that interventions that target motivation are likely to be successful even in populations with compromised cognitive abilities.

Limitations

Despite it being a frequently used measure of self-control (Hagger et al., 2010), using the attention control video task has been criticised (Lurquin, Michaelson, Barker, Gustavson, von Bastian, Carruth, & Miyake, 2016; Lurquin & Miyake, 2017). Specifically, it could be suggested that in the control condition participants may have attempted to memorise the words leading them to apply more effort in the task than initially intended. Additionally, we also did not assess the extent in which participants actually followed instructions in the self-control condition and successfully ignored the words. Despite this, the current study did find performance differences between the groups that did and did not apply self-control in the first task. To strengthen these findings however future research, which employs this task could also implement eye tracking during the task to check where the participant looked on the screen (Lurquin et al., 2016).

Another limitation stems from the comparison of older aged adults to a younger group – aged 18-20 years - of participants that might be considered sub-mature, in terms of their brain development; the frontal brain regions, responsible for self-control, are still developing at this age (Sowell, Thompson, Holmes, Jernigan & Toga, 1999). The frontal lobes (Fuster, 2002), particularly the PFC, matures continually until approximately after the age of 20 (Diamond, 2002) and continued myelination of the PFC occurs between 20 and 30 years of age (Paus, Collins, Evans, Leonard, Pike, & Zijdenbos, 2001). Therefore it could be suggested that examining sequential self-control performance with participants aged 18-20 years might not accurately reflect self-control ability in general and the typical adult population. However, it is important to note that this is a concern for all previous research on self-control and thus the current study has actually been additive to the literature by examining a wider age range of participants in order to move away from solely assessing self-control ability in a sub-mature population.

Conclusions

Filling a research gap, we examined whether there were any age related differences in one's ability to apply self-control over time by recruiting a wider age range of participants. We also examined the potential moderating effects of intrinsic motivation on self-control performance across two sequential tasks. Examining response time, the findings revealed that completing the initial task that required self-control led to a slower response in the subsequent Stroop task and older aged participants were more vulnerable to this. This is consistent with previous research which showed that executive functions strongly suffer and decline with age. Even though in the current study the relationship between age and motivation failed to reach significance, overall motivation more strongly predicted self-control performance for older than younger aged participants. We speculate that this might be to do with the allocation of resources, due to cognitive tasks being costlier for older aged adults and therefore the need to ensure that the allocation of resources is worth the cost; high motivation is needed for this task engagement.

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Paper seven: The relationship between motivation and self-control: does manipulating task interest restore a temporary impairment in self-control following prior exertion?

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Abstract

Self-control plays a vital role in everyday life and social interaction, and refers to the intentional act of altering ones' responses, such as behaviours, thoughts, and emotions. Self-control is prone to failure and research shows that engaging in self-control continually over time – typically across two sequential tasks – results in a temporary impairment in performance in the second task. Research suggested this stemmed from a reduction in intrinsic motivation and the reluctance to allocate resources to a second task. The current study explored this by manipulating intrinsic motivation through priming task interest and enjoyment. Using a between subjects design, the manipulation was administered to half the sample (Total N = 60) between two sequentially completed self-control tasks; a Stroop task (control vs self-control) and antisaccade task. The physiological mechanisms behind any effect of motivation on self-control ability were explored by analysing eye-blink rate as a proxy marker for dopaminergic activity and measuring salivary alpha amylase levels as a marker of activity of the sympathetic nervous system. The results showed that those that completed the incongruent Stroop task and were primed with task interest made faster antisaccade responses than those not primed. Overall, the high motivation group had a higher eye blink rate, indicating greater dopaminergic activity, suggesting a link between dopamine, motivation and self-control performance. Those in the high motivation group produced a lower amount of salivary alpha-amylase indicating reduced SNS activity, when motivated. Motivation thus influenced self-control performance over time and – to the author's knowledge – was the first study to explore potential underlying mechanisms using bio-markers of dopaminergic activity and nervous system activation. Research is needed to corroborate and explore these findings further.

Key words: self-control, glucose, motivation, dopamine, salivary alpha amylase

The relationship between motivation and self-control: does manipulating task interest restore a temporary impairment in self-control following prior exertion?

Self-control is applied widely in everyday life (Hoffman, Baumeister, Foerster, & Vohs, 2012) and refers to the ability of intentionally regulating and overriding impulsive actions (Lee, Chatzantarsis & Hagger, 2016) such as controlling emotions and behaviours (Baumeister, Vohs & Tice, 2007). Research shows that individuals have difficulty continually exercising self-control. This was demonstrated in participants' ability to perform two consecutive self-control tasks; performing the first task successfully but displaying a temporary impairment in self-control ability in the second.

The resource depletion theory/strength model of self-control (Baumeister et al, 2007) suggested that this stemmed from a reduction in the availability of a limited energy resource; employing self-control gradually depletes this resource resulting in a weakened subsequent ability to perform a self-control task. This finding was consistently reported across over 80 studies using a sequential self-control task paradigm; completing an initial self-control (vs. control) task typically produced a temporary deterioration in performance in a second self-control task (see meta-analysis by Hagger, Wood, Stiff, & Chatzisarantis, 2010). However, more recently, research studies have failed to replicate these observations, sparking debates about the robustness of this response (Hagger & Chatzisarantis, 2016; Carter, Kofler, Forster, & McCullough, 2015).

Establishing whether there was actually a physiological resource that fuelled self-control, research proposed the energy substrate was glucose. For example research showed that completing a self-control task led to a reduction in peripheral blood glucose levels (Fairclough & Houston, 2004) and glucose administration had a restorative effect on one's ability to apply self-control in a subsequent task following prior exertion (Gailliot et al., 2007).

However the peripheral changes in blood glucose observed were reasoned to not reflect glucose changes centrally, i.e. the utilisation of glucose by the brain during cognitively effortful tasks (Messier, 2004; Kurzban, 2010); changes centrally are too subtle for differences to be observed based on level of cognitive effort expended (Kurzban, 2010). Further, evidence failed to observe a significant reduction in peripheral blood glucose levels following self-control exertion (Dang, 2016a; Kelly, Sünram-Lea & Crawford, 2015). Evidence has thus failed to show that the digestion of glucose to fuel self-control ability is necessary (Kurzban, 2010; Molden et al., 2012; Sanders, Shirk, Burgin, & Martin, 2012; Lange & Eggert, 2014). And a recent meta-analysis of the literature observed no direct relationship between glucose availability and self-control performance (Dang, 2016a).

Alternatively motivation was argued to be a key predictor of self-control, with high motivation having a counteracting effect on any temporary deficiency in performance in a second act of self-control following prior exertion (Inzlicht & Schmeichel, 2012; Inzlicht, Berkman & Elkins-Brown., 2014). For example the resource allocation account (Beedie & Lane, 2012) posits that a temporary deterioration in self-control does not stem from resource depletion but from a change in resource allocation based on motivation level. In particular, if a task is deemed to be interesting and/or important one will be motivated to assign resources to a task, despite the earlier application of self-control. Similarly, the process model/shifting priorities account takes a motivational but non resource perspective and posits that a weakened performance in a second self-control task stems from an alteration or shift from one having the motivation to control and suppress one's impulses in the first task to this being reduced in the second task. If however one is highly motivated to engage in the second task this shift is counteracted and self-control is continually applied in a subsequent task (Inzlicht & Schmeichel, 2012; Inzlicht et al., 2014; Inzlicht & Schmeichel, 2016).

Consequently, altering the way in which tasks are perceived i.e. increasing their value or personal relevance may result in subsequent self-control performance being maintained or enhanced despite prior exertion (Inzlicht, et al., 2014; Kazén, Kuhl, & Leicht, 2014). For example labelling a task enjoyable led to an enhanced performance (Werle, Wansink & Payne., 2014). This is consistent with our previous findings (Kelly, et al., 2015); possessing high levels of self-reported intrinsic motivation – assessed with the intrinsic motivation inventory (McAuley, Duncan & Tammen, 1989) - led to better performance in a second task of self-control following the earlier application of self-control in a dissimilar self-control task.

The current investigation proposed to examine this by directly manipulating motivation between the administration of two sequential self-control tasks and observe whether increasing motivation in this way enhances self-control performance in a subsequent antisaccade task (Hallett, 1978) despite the earlier application in the Stroop task (Stroop, 1935). For the purpose of this investigation, motivation was manipulated intrinsically. Intrinsic motivation refers to the engagement in tasks due to their inherent interest or enjoyment (Ryan & Deci, 2000). This fitted consistently with our previous findings (e.g. Kelly et al., 2015; Inzlicht, et al., 2014; Kazén et al., 2014) and both the resource allocation account (Beedie & Lane, 2012) and shifting priorities account (Inzlicht et al., 2014; Inzlicht & Schmeichel, 2016).

The manipulation used in the current investigation was based on the methodological design of previous research studies, which framed the second task in a sequential two task design to be both significant and interesting. For example in one of these studies, participants were told – after completing a thought suppression task - that completing a second task would provide scientific evidence for the treatment of Alzheimer's disease, subsequently persisted for a longer time in the task (Muraven & Slessareva, 2003). Similarly, Vohs, Baumeister and

Schmeichel (2012) told participants that the research would inform a marketing promotion titled “The Science Behind Better Lives”, which would improve general welfare, happiness, and health. Supporting Muraven and Slessareva (2003) those informed displayed enhanced performance in a second task of self-control despite earlier exertion.

Consequently the current study manipulated motivation in a comparable way by attempting to tap into participants’ interest in the second task – the antisaccade task (Hallett, 1978) - by providing information about current research that explores the use of eye movements for the diagnosis of Alzheimer’s disease. (Crawford, Higham, Mayes, Dale, Shaunak & Lekwuwa, 2013)

Additionally we wanted to explore the underlying potential physiological mechanisms i.e. the physiological activities that might be associated with cognitive- motivational states (Evans, Boggero & Segerstrom, 2016). These are now discussed.

Motivation and salivary alpha amylase

Salivary alpha amylase (sAA) - a critical protein produced with saliva (Rohleder & Nater, 2009) - has the main function of digesting carbohydrates (Baum, 1993); however, evidence (Chatterton, Vogelsong, Lu, Ellman, & Hudgens, 1996) suggests that it can also be used as an indicator of sympathetic nervous systems (SNS) activity (see Nater & Rohleder, 2009 for a review of the literature). Thus, stressful or demanding situations are argued to activate the SNS with sAA being a useful measure of such activation (Rohleder, Nater, Wolf, Ehlert & Kirschbaum, 2004; Maruyama et al., 2012). There are very few studies that fail to observe a significant increase in the release of sAA in response to stressful situations; higher during both physical and psychological stress (Chatterton et al., 1996). More specifically, sAA has been suggested as a biomarker of the noradrenergic component of SNS activation (Ditzen, Ehlert, & Nater, 2014; Kuebler, von Känel, Heimgartner, Zuccarella-Hackl, Stirnimann, Ehlert, & Wirtz 2014; Rohleder and Nater, 2009; Wiemers, Sauvage, Schoofs, Hamacher-Dang, & Wolf, 2013).

Arousal has been linked to the activation of sympathetic nervous system (SNS) which has subsequently been associated with motivational responses to challenge and threat (Blascovich & Mendes, 2000). Challenge in particular is associated with SNS activation and leads to improved performance in tasks (Dienstbier, 1989). Activation of the SNS can be measured with levels of salivary alpha amylase (sAA). Thus increased motivational responses to challenge should increase sympathetic arousal in terms of an increase in sAA levels (Jamieson, Mendes, Blackstock & Schmader, 2010). Therefore in a similar way, it could be speculated that in this study any observed high levels of motivation facilitated stimulation of the sympatho-adrenomedullary axis (SAM axis) of the SNS leading to an increase in energy production (Evans et al, 1986) and a boost in energy to tasks that one was motivated to complete.

Thus, applying this to motivation, one could speculate that heightened motivation induces an acute stress response, leading to SNS activation. An increase in the release of sAA has been found to be related to levels of performance (Bishop, Walker, Scanlon, Richards, & Rogers, 2006); high release was paired with a better performance. Thus one would predict that as heightened motivation levels enhances performance that this would be paired with an increase in the production of sAA. Alternatively one could speculate that heightened motivation reduces stress producing a reduction in sAA, leading to heightened performance. Schwab, Wolf and Memmert's (2015) observed that experiencing regulatory fit (performing a goal that is in line with one's beliefs; Higgins, 2000), heightened motivation and reduced stress levels leading to the production of less sAA and subsequently improved performance.

The current study aimed to explore both perspectives and measured sAA by collecting unstimulated saliva samples from salivettes three times during the experimental session;

before and after the first task and after completion of the second task. This is the most common technique for collecting saliva, where by saliva is then extracted using centrifugation (Rohleder & Nater, 2009).

Motivation and dopamine (eye blink rate)

Further, the current study explored the potential relationship between dopamine and intrinsic motivation. Earlier research suggested dopaminergic function was solely linked to reward processing, however this has recently changed (Salamone & Correra, 2012), with research pointing to role of dopamine in directing energy expenditure to an act which is considered interesting and/or important (Salamone, Correa, Farrar, & Mingote, 2007) leading to its' successful completion (Beeler, Frazier & Zhuang, 2012). Previous research (e.g. Peckham & Johnson, 2015; Dang, Xiao, Liu, Jiang and Mao, 2016) measured dopaminergic activity by recording rate of eye blinks in a saccadic eye movement task as a proxy marker. Eye blink rate (EBR) provides a useful indicator of dopaminergic function particularly in the striatum and the extent that one wishes to exert cognitive effort when motivated (Kroemer, Guevara, Teodorescu, Wuttig, Kobiella, & Smolka, 2014; Peckham & Johnson, 2015). Eye blink rate is considered a valid and useful proxy marker of dopaminergic activity and is easy to measure (Karson, 1983; Jongkees & Colzato, 2016). Patients with Parkinson's Disease, a condition, linked with an impairment in dopaminergic activity and a general weakening in motivation (Foerde, Braun, Higgins, & Shohamy, 2014) displayed a lower EBR compared to healthy controls (Karson, 1983).

Applying this to sequential self-control task performance, Dang et al (2016) observed a sustained eye blink rate (neither too high nor too low), which they argued indicated sustained dopaminergic acivity was most optimal for counteracting any temporary deficiency in self-control ability in an antisaccade task following exertion in a Stroop task. This required further exploration, thus the current study explored the relationship between dopaminergic activity, motivation and self-control ability.

For the purpose of this investigation EBR was measured in a separate task rather than within the saccade tasks as the nature of the tasks i.e. making a saccadic eye movement in response to a target, might have a confounding effect on the rate of eye blinks. This posed problems during an anagram task as successfully expending effort in a task and following the task instructions conflicted with assessments of EBR (Doughty, 2001; Caplan, Guthrie & Komo, 1996).

Beliefs about self-control capacity and willpower

Previous research observed differences in one’s vulnerability to self-control deficiency following prior exertion based on whether one believed self-control was limited. For example, Job, Dweck and Walton (2010) revealed that participants biased (via a questionnaire) towards the limited view demonstrated the typical response trajectory posited by the resource depletion theory; a temporary deficiency in performance in the second of two concurrent self-control tasks. This finding was not however captured in those that believed self-control ability had no limit.

This was reiterated in a later study, which employed an identical method for manipulating beliefs about willpower capacity that involved the administration of a questionnaire that biased participants to one view or the other. Specifically, Miller, Walton, Dweck, Job, Trzesniewski, & McClure (2012) observed that during a twenty minute working memory task, - which was split into two sections - those led to believe that willpower was limited, showed a temporary deterioration in performance in the second section of the task. However, participants that were exposed to the idea that willpower had no limit showed an improved level of performance in the second part.

Drawing on these investigations and those in which a questionnaire was used to assess one's existing views about willpower capacity (Job et al., 2010; Job, Walton, Bernecker, & Dweck, 2013); the current study explored the moderating effects of beliefs about willpower on self-control performance over time.

The current investigation

The study examined whether any impairment in self-control performance in a second task – the antisaccade task – following prior exertion in a Stroop task (Stroop, 1935) was restored for those high in motivation (primed with task interest). Reflecting Muraven and Slessareva's (2003) design, we manipulated motivation by informing participants about the research on saccadic eye movement tasks and Alzheimer's disease (Crawford et al., 2013). We explored possible physiological mechanisms involved in any motivational effects, by measuring the potential involvement of sAA and dopamine. To reflect our previous study designs (Kelly et al., 205; Kelly, Crawford, Gowen, Richardson, & Sünram-Lea, 2017), self-reported levels of motivation were also measured using the intrinsic motivation inventory. Further, to maintain consistency with our previous study (Kelly et al., 2015), along with the antisaccade task (Hallett, 1978) we also administered the proscaccade task (eye movements are directed towards the target). This assessed whether any performance differences arose solely for inhibitory ability (in the antisaccade task) or more generally to saccadic eye movements. Further, due to recent findings on willpower beliefs, we explored whether holding a limited compared to limitless resource view about self-control capacity (Job et al, 2010; 2013; Miller et al, 2012) influenced sequential self-control task performance. Following mixed views about the role of glucose in self-control performance we measured peripheral levels of blood glucose before and after initial task completion and after the second measure of self-control. An increase would support motivational accounts i.e. when motivated energy is allocated to a task (Beedie & Lane, 2012; Kazén et al., 2014). A decrease would support the resource depletion theory; engaging in self-control produces a reduction in the resource responsible (Baumeister et al., 2007; Gailliot et al., 2007).

Method

Design

The study employed a 2 (initial condition; self-control vs. control) x 2 (motivation condition; task importance vs. neutral) x 2 (saccade task; prosaccade & antisaccade) x 3 (time of blood glucose measurement; one, two, three) x 3 (salivary alpha amylase; one, two, three) mixed factorial design with repeated measures on the third, fourth and fifth factors.

Participants

Sixty-six healthy young adults aged between 18-35 years were recruited. However six participants had to be removed from the analysis; five participants failed to successfully complete the eye movement tasks and one participant withdrew from the study. This left a final sample of 60 participants (23 male & 37 female) with an average age of 24.13 years (SD = 4.81). Participants were screened before the study to ensure none had Diabetes Mellitus and none were pregnant, seeking to become pregnant or lactating. Participants were randomly allocated to both the initial task and motivation conditions. Ethics approval was granted by Lancaster University Ethics Committee and all participants gave written informed consent in line with the Declaration of Helsinki.

Materials

Initial task: Stroop task: A computerised version of Wallace and Baumeister's (2002) Stroop task was administered. Participants had to respond to the ink colour of the word as precisely and as rapidly as possible by pressing certain keys on the keyboard, as well as stating their response out loud. The duration of the task was approximately 4 minutes 30 seconds (135 colour words).

Control (congruent): Colour words were matched to the ink colour they were written in.

Self-control (incongruent): Colour words and the ink colours of the words were mismatched. For trials when the word was presented in red ink, participants had the additional instruction of stating the word rather than the words' ink colour.

Dependent measure of self-control (second task): Saccade tasks (Hallett, 1978): Eye-movements were recorded via a camera (Eye link II for 51 participants and due to technical issues with the Eye link II, the Eyelink 1000 was used for 9 of the participants) attached to a computer. Participants placed their head on an adjustable chin rest, which was positioned 57cm away from the computer screen and camera. Participants completed a series of trials in which a green target was presented to the left or right of the computer screen. For every trial a fixation cross appeared in the centre of the screen and after 1,000 ms, the green target (.6° diameter) appeared 8° to the left or right of the fixation cross. Both the target and cross stayed on the screen for 1,000 ms (overlap), and a 1,500-ms interval preceded the next trial. Target location was randomised and it appeared on either side with equal frequency.

Overlap Prosaccade task: Participants were instructed to direct their eyes towards the green target.

Overlap Antisaccade task: Participants were instructed to direct their eyes away - and to the opposite side of the screen (left or right) – to the green target as quickly and as accurately as possible.

Eye blink rate (EBR) saccade task

To measure EBR, a two minute saccade task was administered. Participants were presented with a fixation cross in the middle of the screen and were instructed to look at the cross and sustain their attention on the cross until it disappeared from the screen. Eye blinks were recorded continuously for a two minute period. To control for the possible confound of time of day, experimental sessions were scheduled to occur no later than 17:00, as previous research observed eye blinks to increase in the evening (Barbato, della Monica, Costanzo, & De Padova, 2012).

Motivation manipulation

Participants in the high motivation condition were presented with the following information in written format before being provided with the saccadic eye movement task instructions on the computer screen (see text below). Participants in the no motivation/neutral condition only received the task instructions.

"You will now be asked to complete some eye movement tasks. By participating in these tasks this will enable us to carefully assess how the eyes are controlled by the brain, which is important as we hope that this will help us to develop more reliable assessments that can be used to assess cognitive and memory-related impairments in older adults such as Alzheimer's disease. A full understanding of the causes of Alzheimer's disease is not yet known and we also cannot predict who will develop Alzheimer's disease or other forms of memory impairment. Previous and ongoing research however by Dr. Trevor Crawford and colleagues (Crawford, Higham, Mayes, Dale, Shaunak & Lekwuwa, 2013) have identified differences in how people with Alzheimer's disease perform the eye movement tasks that you are now being asked to complete. Thus one of the purposes of this study is to provide scientific evidence,

which can then later be used to help us to determine the effects of Alzheimer's disease on eye movements in older adults."

Blood glucose level measurements

Peripheral levels of blood glucose were recorded using the ExacTech glucose measuring device at baseline, after engaging in the Stroop task and after completion of the saccadic eye movement tasks. This measuring tool is employed regularly by those with diabetes mellitus and is deemed to have high measurement sensitivity (Rebel, Rice & Fahy, 2012). Further, there is a strong relationship between glucose measured in the capillary (finger prick) and AV blood (Dye et al., 2010).

Saliva sample collection

Salivary alpha amylase was measured following the collection of saliva samples (Salimetrics; Kinetic enzyme assay kit) using the Salivette saliva sampling device (Sarstedt Ltd, Leicester, UK); a small test tube fitted with an inner receptacle containing a sterile cotton wool bud. Participants removed the cotton wool bud and provided unstimulated saliva samples by placing the cotton wool bud under their tongue for a timed period of two-minutes before replacing it back in the test tube. All saliva-contaminated waste was placed in a yellow biohazard bag and disposed of via Lancaster University's Biology Autoclave system. Test tubes were sent to School of Applied Sciences, University of Huddersfield within 24 hours, where the saliva-cotton wool was centrifuged and analysed.

Intrinsic Motivation Inventory (IMI) [Ryan, 1982; McAuley, et al., 1989]

Self-assessed levels of intrinsic motivation were recorded with a 36 item IMI. Participants made their responses using a 7-point-Likert scale, with answers ranging from 'not at all true' to 'very true'. Example statements that required a response included, 'I enjoyed doing this activity very much', 'This activity was fun to do', 'I did this activity because I wanted to' and 'I would be willing to do this again because it has some value to me'. Responses were gathered in order to provide an overall assessment of how motivated participants were to complete the saccade tasks (Ryan, 1982; McAuley, et al., 1989; Li, 2004).

Limited resource view questionnaire (Job, Dweck & Walton, 2010)

Participants completed 12 questions, which assessed their beliefs about the limited capacity of self-control. Responses were made using a 6 point Likert scale and ranged from 'strongly agree' to 'strongly disagree'. Statements that required a response included 'After a strenuous mental activity, your energy is depleted and you must rest to get it refuelled again' to 'If you have just resisted a strong temptation, you feel strengthened and you can withstand any new temptations'. Responses were summated and averaged to provide an indication how limited willpower was considered to be.

Procedure

Prior to the session, participants were instructed to have fasted for at least two hours (refrained from consuming any food or drink except water). At the start of the experimental session, participants were asked some demographic questions (regarding age, height and weight) and asked to sign an informed consent sheet before then completing either an incongruent (self-control/depletion) or congruent (control) version of the Stroop task. Participants in the motivation condition were then provided with background information about the eye movement tasks. Those in the neutral (no motivation) condition did not receive this information. All participants then performed the EBR saccadic task, followed by the prosaccade and antisaccade tasks. The prosaccade task was completed first to remove the possible confound of carry over effects across the prosaccade and antisaccade tasks (Roberts, Hager & Heron, 1994). Finally the intrinsic motivation inventory and limited resource view questionnaire were completed before being debriefed. In addition, peripheral levels of blood glucose were measured from the fingertip of participants along with saliva samples at three occasions (baseline, after the Stroop task and after the completion of the eye movement tasks).

Statistical analysis

Saccade performance was measured with two eye movement parameters; response time (for both saccade tasks) and erroneous response rate (for the antisaccade task only). Response times were calculated using the saccadic eye movements that followed target onset and had amplitudes of greater than 2° and were between 80-500 ms (to remove saccades that were considered anticipatory or late). Directional errors were measured by calculating the total number of errors (incorrect saccades made towards rather than away from the target) made across the trials in the antisaccade task.

In R (R Core Team, 2015) using the package lme4 (Bates, Maechler, Bolker, & Walker, 2015), response time was analysed with linear mixed-effects modelling and erroneous responses with generalised linear mixed effects modelling (due to the binary outcome). Within the models, participants were added as a random effect. Type of saccade task (for response time only) as well as the initial task completed and motivation condition were all added as fixed effects. Motivation level was then added as a covariate along with limited beliefs about willpower.

Blood glucose levels and salivary alpha amylase (measured at three time points) were all analysed separately using linear mixed effects modelling, adding participants as a random effect and initial condition, motivation condition, and time of reading as fixed effects. Eye blink rate was also analysed using linear mixed effects modelling, adding participants as a random effect and initial condition, motivation condition, as fixed effects to the model.

Results

Manipulation check (see Figure 1)

The Stroop task requiring self-control was reported to require more effort [β = -2.20, t (58) = -6.39, p = .000] and was more frustrating to complete [β = -1.20, t (58) = -3.22, p = .00] than the control/basic version of the task. There were no differences between the two tasks in the level of tiredness felt following completion [β = 3.73, t (58) = .00, p = 1.00] nor in how pleasant the administered task was [β = -.03, t (58) = -.11, p = .92]. Participants performed the Stroop task that required self-control with a lower level of accuracy (M = 86.46, SD = 12.80) than the group that completed the control version (M = 99.23, SD = 1.41) of the task [β = 12.77, t (58) = 5.43, p = .00].

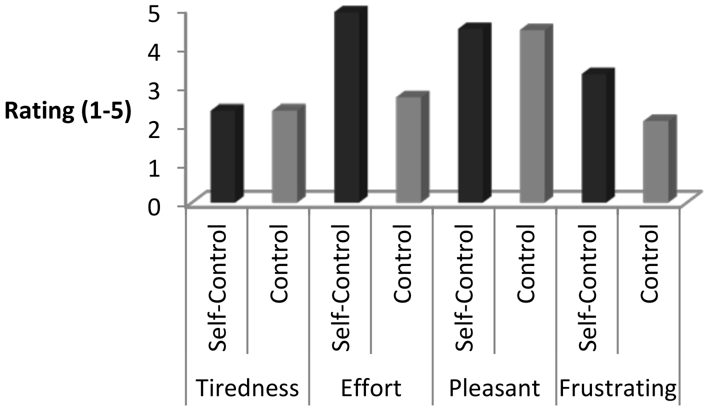

*Figure 1:1*Ratings for the manipulation check as a function of the initial task completed.

Saccade performance

Speed of response (RTs)

Initially fitting a model with participants as a random effect and task type as a fixed effect revealed task type to be a significant predictor of response speed [β = -55.30, SE= 2.16, t = -25.60]; the prosaccade task was performed faster than the antisaccade task. Adding initial task as a fixed effect reported no effect but there was a significant initial task x saccade task interaction [β = 8.70, SE= 4.31, t = 2.00], with this model being a better fit for the data [χ^2 = 606.97, df = 3, p < .001]. Examining the interaction further, in the self-control condition, the prosaccade task was completed at a significantly faster rate than the antisaccade task [β = -51.00, SE= 3.08, t = -16.50]. This was also extended to the control condition [β = -59.70, SE= 3.01, t = -19.80]. Adding motivation condition (high versus low) to the model produced a significant initial task x motivation condition x saccade task interaction [[β = -35.35, SE= 8.60, t = -4.10]], with this model being a significantly better model fit than the intercept (null) model [χ^2 = 634.48, df = 7, p < .001]. Adding self-reported levels of intrinsic motivation, and limited beliefs about willpower to the model did not produce any further significant effects.

Exploring the interaction further, specifically examining saccade response time based on the saccade task completed, revealed only effects of the initial task completed and motivation condition on antisaccade response speed; this was not extended to prosaccade responding. Specifically, an initial task x motivation condition interaction was reported [β = 46.99, SE = 17.28, t = 2.72] (see figure 2). Findings revealed that for those that applied self-control in the initial task, and were in the low motivation group, antisaccade responses were slower compared to those in the high motivation group [β = 41.30, SE = 11.70, t = 3.52]. No effect of motivation condition was observed following the completion of the initial control task [β = -5.75, SE = 12.71, t = -0.45]. Examining the group that received the motivation prompt (high motivation), those that engaged in self-control in the initial task subsequently made faster antisaccade responses than the group that completed the initial control task [β = -39.92, SE = 13.76, t = -2.90].This was not extended to the low motivation group [β = 7.18, SE = 10.50, t = 0.70]

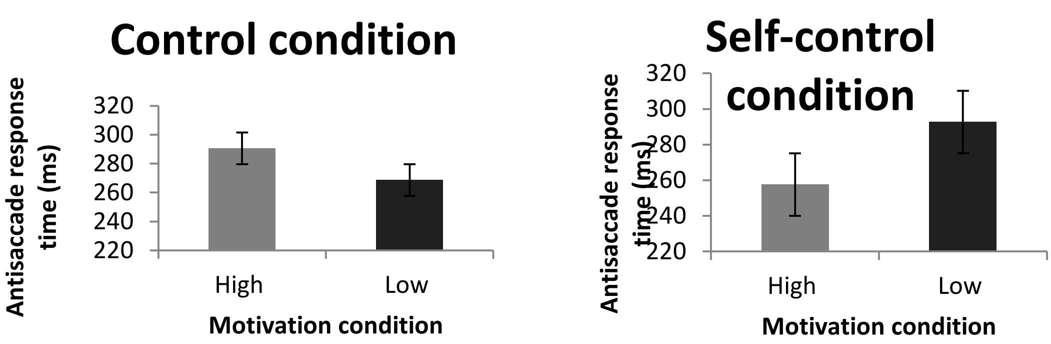

Figure 2: Antisaccade response time as a function of motivation and grouped by initial task.

Erroneous antisaccade responses relative to correct responses

Initially fitting a model with initial task completed as a fixed effect and participants as random effects revealed an approaching significant effect of task [β = 0.61, SE= 0.32, z = 1.93, p = .05, Bayes Factor in favour of the alternative hypothesis]; more errors were committed after completion of the initial task that required self-control (incongruent Stroop task) than after the control task (see figure 3). Adding motivation condition produced no significant effect of motivation or interaction [p > .05]. The effect of initial task was still significant with more errors committed by those that completed the initial self-control task [p = .05]. Adding motivation and then limited beliefs about willpower as covariates to the model produced no further significant main or interaction effects.

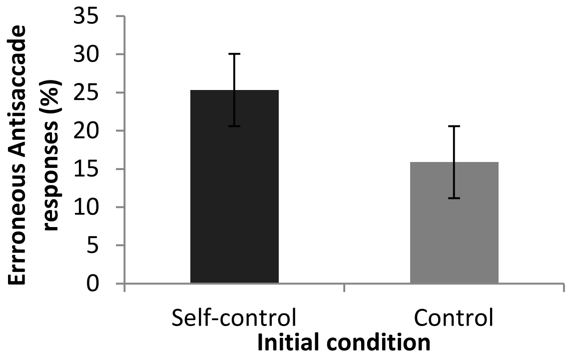

Figure 3: Percentage antisaccade errors based on the initial task completed

Motivation condition

Examining the relationship between motivation condition and self-reported levels of intrinsic motivation, a model was fitted with participant as a random effect and motivation condition as a fixed effect. This revealed motivation condition to not be a significant predictor of motivation level [β = 0.10, SE= 0.16, t = 0.60, p = 0.54]; those primed with task interest were no more intrinsically motivated (M = 4.52, SD = 0.64) than those not primed (M = 4.43, SD = 0.63). Adding initial task condition to the model produced no significant main or interaction effects ($p > .05$).

Blood glucose levels

Initially fitting a model with participant as a random effect and time of blood glucose reading as a fixed effect, revealed no significant effect of time of reading [$F (2, 180) = .64$, $p = .53$]. Adding initial condition and motivation condition produced no main or interaction effects ($p > .05$).

Eye blink rate

Initial task was not a significant predictor of eye blink rate [β = -3.10, SE= 6.86, t = -0.45, p = .65]. Adding motivation condition to the model revealed no main or interaction effects [$p > .05$]. A model fitted with solely motivation condition as a fixed effect revealed this to not be a significant predictor of eye blink rate [F (1, 58) = 3.23, p = .07] but inspection of the means indicated that those in the low motivation group made 12.03 fewer eye blinks than those in the high motivation group [β = -12.03, SE= 6.69, t = -1.80, p = .08, Bayes Factor in favour of the alternative hypothesis]. Adding self-reported levels of motivation to the model produced no significant effect of motivation [β = -7.20, SE= 5.42, t = -1.33, p = .19] with motivation condition producing the same effect [β = -88.95, SE= 47.36, t = -1.88, p = .07, Bayes Factor in favour of the alternative hypothesis]; those in the high motivation group produced a higher rate of blinks (see figure 4). There was no motivation x motivation condition interaction [p > .05].

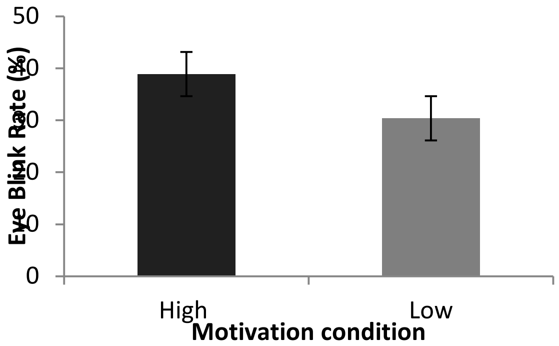

Figure 4: Eye blink rate as a function of motivation condition

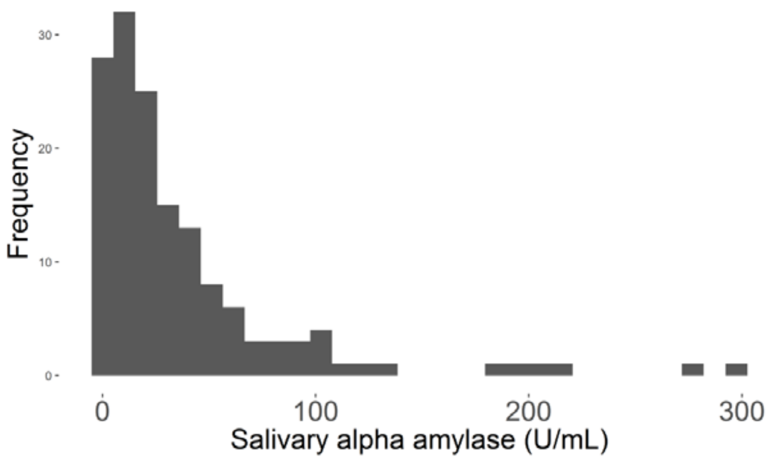

Figure 5: Histogram of the distribution of measurements of salivary alpha amylase

Salivary alpha amylase

The observed sAA data (see figure 5) represented the typical response pattern data gathered on sAA, which generally does not follow a normal distribution but is widely varied and positively skewed (Rohleder & Nater, 2009). For some of the salivettes the saliva samples that were obtained were too low and had to be removed from the analysis. In total 24 participant samples had to be removed, resulting in sAA analysis for 36 of the participants' samples. In all the models we added baseline levels of sAA as a covariate to account for the law of internal values. We first fitted a model with time of saliva reading as a fixed effect and participants as a random effect, which revealed time of reading to be an approaching significant predictor of sAA [F (2, 108) = 2.95, p = .06]. Inspection of the means revealed that measurements taken at time three were higher than at time one [β = -19.12, SE = 8.05, t = - 2.38, p = .02]. Adding initial task completed as a fixed effect revealed no main effect of task [F (1, 108) = 1.73, p = .19]. There was no significant task by time of reading interaction [F (2, 108) = .42, p = .66]. Adding motivation condition to the model revealed motivation condition to be an approaching significant predictor of level of sAA irrespective of initial condition [F (1, 108) = 3.48, p = .07]; those high in motivation (M = 32.69, p = 27.86) produced lower levels of sAA than those low in motivation (M= 47.23, SD = 46.97). Fitting a model with time of reading and motivation condition as fixed effects and participants as a random effect revealed a significant effect of motivation condition [F (1, 108) = 4.85, p = .03]; those high in motivation produced 25.83 U/mL less sAA than those low in motivation [β = -25.83, SE = 11.02, t = -2.35, p .02] but no motivation x time of reading interaction [F (2, 108) = 1.36, p = .26]. Examining the interaction however revealed differences in level of sAA based on motivation condition only at measurement time three [β = -25.99, SE = 14.78, t = -1.76, p .09; Bayes factor in favour of alternative hypothesis]; those high in motivation produced less sAA (M = 37.17, SD = 32.01) than those low in motivation (M = 63.52, SD – 57.56) irrespective of initial task completed. This was not extended to times one and two (p > .05) (see figure 6).

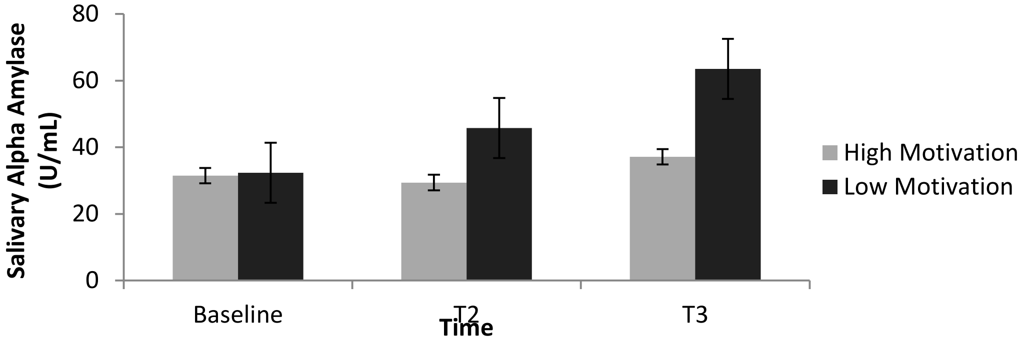

Figure 6: Measurements of salivary alpha amylase by time of reading and motivation condition

Discussion

The current study explored the role that motivation – and in particular intrinsic motivation - appears to play on one's ability to apply self-control successfully across two sequential tasks. The resource allocation (Beedie & Lane, 2012) and shifting priorities accounts (Inzlicht et al., 2014) suggest that the typical finding of an impairment in performance in the second of two self-control tasks, stems from a lack of motivation based on task interest and enjoyment. This lies in contrast to the resource depletion theory (Baumeister et al., 2007) that states that self-control depletion is reflective of a reduction in the availability of a limited resource, which directly fuels self-control, such as glucose (Gailliot et al., 2007). We previously observed that self-reported differences in level of intrinsic motivation counteracted the adverse effect that performing an initial self-control task had on subsequent self-control exertion (Kelly et al., 2015). We explored this further by observing whether actually manipulating intrinsic motivation, through priming task interest and importance had a restorative effect on self-control performance following prior exertion.

Further, the current study attempted to address why motivation appears to have a counteracting effect on self-control depletion in terms of the physiological mechanisms responsible (Evans et al., 2016). One possibility explored was the role of dopamine in motivated energy expenditure towards a task. Eye-blink rate (EBR) was used as a proxy measure of dopaminergic activity (Karson 1983). Alternatively being motivated might lead to an acute stress response and subsequent SNS activation. A potential biomarker for this activation was sAA so measurements of this were taken to assess any potential association with high motivation.

Findings revealed that those in the high motivation condition (primed with task interest) made faster antisaccade responses following the completion of the initial incongruent Stroop task that required self-control than those in the low motivation condition. This was not extended to the prosaccade task or those that completed the control task. Supporting motivational accounts (Beedie & Lane, 2012; Inzlicht et al., 2014) despite prior self-control exertion, high intrinsic motivation through priming interest and importance in completing the saccade tasks, led to an enhanced antisaccade performance.

An examination of EBR, revealed a possible role for dopamine in the restorative effect of high motivation on antisaccade response speed. Findings revealed that those in the high motivation condition produced more blinks than those in the low motivation condition; being primed with task interest resulted in a higher level of recorded blinks. A Bayes factor analysis favoured the alternative hypothesis, promoting confidence in the association between high motivation and a higher eye blink rate. Based on previous evidence on the relationship between dopamine and eye blink rate and effortful task performance (Karson, 1983), these findings suggested that priming task motivation produced greater dopaminergic activation. This is supportive of the argument that dopamine resulted in the injection of energy into the subsequent antisacacde task leading to successful performance; faster responding.

However the association between eye blink rate and motivation was observed irrespective of the initial task completed. Therefore overall those that received the motivation manipulation produced more blinks with only those that had previously exerted self-control performing better in terms of faster responses in the antisaccade task than those low in motivation.

Recent literature observed a relationship between dopaminergic activity – using EBR as a proxy marker of this - and self-control depletion but reported that a medium EBR was most effective for restoring self-control depletion; increased response accuracy (Dang et al., 2016). However in the current study EBR was not observed to have a direct effect on antisaccade performance only those in the motivation condition performed the antisaccade at a faster rate than those in low motivation condition following prior self-control exertion and this group also had a higher EBR, which is greater dopaminergic activation.

The analysis of salivary alpha amylase (sAA) - an indicator of SNS activity - showed that those in the high motivation condition produced significantly less sAA at the final time of measurement than those low in motivation. This was regardless of the amount of effort expended in the initial task; overall those in the high motivation condition produced less sAA. Evidence for less SAA activation when motivated was observed by Schwab, et al (2015); when motivation was low, sAA activation was higher. Schwab et al (2015) argued that being highly motivated means one is less stressed as there is more regulatory fit in the situation. According to Higgins (2000), interest in performing a task and thus high intrinsic motivation produces this regulatory fit effect. We could thus speculate that the high motivation condition provided a situation of regulatory fit as interest and importance in performing the second task was primed. According to prior research, this then should produce an enhanced performance in tasks. Schwab et al (2015) however did not measure performance. Filling a research gap, the current study showed that when motivated, sAA was lower suggesting participants were less stressed, which also led to enhanced antisaccade performace, relative to those low in motivation. Thus as posited by Schwab et al (2015), stress mediated the relationship between motivation and performance; a physiological response marker i.e. sAA explained why performance increased in tasks that filled their motivational goals as typically stress is lowered during regulatory fit situations (Schwab et al., 2015).

Based on the findings one could speculate that high motivation is mirrored by a physiological response; an increase in dopamine and a lowering or more sustainable level of sAA. The low motivation group had higher sAA levels suggesting that low motivation led to increased stress activation over time whereas those high in motivation were protected against this. Neither physiological response was however modulated by type of initial task completed and level of self-control previously expended. One could speculate that being motivated produces these physiological responses but only when effort has already been expended that motivation produces an increase in performance level as one allocates resources to the task.

However, it is important to note that using salivettes to measure salivary alpha amylase is arguably problematic as it is limited in terms of the amount of saliva that can ideally be collected. This was demonstrated in the samples acquired as we had to remove some due to not enough saliva collected. A more consistent and effective measure for future would be to use the passive drool technique (Navazesh, 1993).

The current study reported no modulating effects of self-reported levels of intrinsic motivation on sequential self-control performance. We thus failed to replicate our previous findings that self-reported intrinsic motivation significantly predicts antisaccade error rate (Kelly et al., 2015; Kelly et al., 2017). This however might stem from a general weakness with relying on self-reported data (Podsakoff, 1986) but also might be due to the additional demands implemented in the study i.e. the novel introduction of both the eye blink task and saliva samples. It was also the first time we actually manipulated motivation into this study design. This meant the session was more demanding and could have accounted for the disparate findings to those observed previously on the moderating effects of self-reported levels of motivation on self-control performance in the antisaccade task.

Results showed that manipulating motivation had an influence on antisaccade performance but only for reaction time, not for error rate. Our previous results observed differences in saccade performance based on error rate. Carter et al (2015) however states that response speed and/or accuracy can both be indicative of measures of self-control performance following prior exertion. Self-control depletion can be measured using either response time or error rate; it is the inherent nature of the paradigm that differing findings are likely to occur (Carter et al., 2015).

However, results did show a difference in performance accuracy based on the initial task completed. Specifically fewer antisaccade errors were made following the completion of the control version of the Stroop task and a Bayes Factor analysis supported this, increasing confidence in these findings. This is supportive of previous evidence (Hagger et al., 2010) and the strength model of self-control, that applying self-control in an initial task leads to a temporary impairment in self-control ability in a subsequent task. This evidence thus adds to the wide debate about the tenability of the ego depletion effect (Dang, 2016b; Hagger & Chatzisarantis, 2016).

There were no direct effects of glucose on self-control performance; no significant changes in glycaemic response occurred following self-control exertion. Thus following self-control exertion, blood glucose levels did not significantly deplete, challenging the resource depletion theory. This is consistent with our previous study (Kelly et al., 2015) and more recent findings (Dang, 2016a). It was however predicted that there might be an association between blood glucose levels and motivation. In particular the resource allocation account (Beedie & Lane, 2012) suggests that the allocation of resources to tasks based on motivation level may result in blood glucose levels staying at a consistent level over time or increasing.

For example, Kazén et al (2014) observed that an increase in motivation was paired with an increase in blood glucose and a subsequent improved self-control performance. The current study provides support for Beedie and Lane's (2012) claims as blood glucose levels stayed consistent across time.

Conclusions

In summary, findings revealed that following self-control exertion in an initial task those primed with task interest and importance (high motivation condition) performed the subsequent antisaccade task at a faster rate than those in low motivation condition (not primed with task interest). Overall those in the high motivation condition produced more eye blinks and less sAA, which tentatively points to some form of physiological mechanism being responsible for the modulating effects of motivation on self-control depletion. This was however irrespective of level of initial self-control expenditure. To the author's knowledge, this was the first study to measure both dopamine and sAA in an investigation into the possible modulating effects of motivation on a temporary deficiency in self-control performance within a sequential self-control task paradigm. This study therefore provided an interesting insight into two possible physiological responses tied to high motivation, which requires further exploration.

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Exploring why a temporary deficiency in self-control ability appears to occur following prior exertion: A discussion

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Exploring why a temporary deficiency in self-control ability appears to occur following prior exertion: A discussion

This thesis explored a behaviour that we frequently use on a daily basis; self-control. This is the ability we have of controlling and regulating our behaviour, overriding one dominant response for another, for example suppressing certain emotions in public, refraining from unhealthy food when on a diet (Baumeister, 2012). It is an executive function involved in the top down processing of control, which requires effort (Diamond, 2013). It is regularly exercised (Hoffman, Baumeister, Foerster, & Vohs, 2012) and important in social interaction.

However, a weakening in self-control ability can occur. Research showed that when completing two sequential tasks that require self-control, typically, the first task is performed well but a temporary impairment in the application of self-control is displayed in the second (Hagger, Wood, Stiff, & Chatzisarantis, 2010). Baumeister, Vohs and Tice (2007) termed this performance pattern ‘ego depletion’ and developed the strength model of self-control to explain this; a waning in self-control performance stems from self-control relying on the availability of a limited energy resource resulting in limited resources available for subsequent self-control exertion. This response trajectory has been demonstrated widely; using a sequential two task depletion paradigm; over 80 studies observed that after applying self-control in an initial task the ability to perform a second self-control task was weakened (Hagger et al., 2010).

However, more recently this notion has been challenged (Carter, Kofler, Forster, & McCullough, 2015; Carter & McCullough, 2014; Luethi, Friese, Binder, Boesiger, Luechinger, & Rasch, 2016; Cunningham & Baumeister, 2016) with findings leading one to question the existence of the ‘ego depletion’ effect i.e. that a temporary deterioration in self-control performance following prior exertion occurs.

The experiments reported in this thesis were therefore designed with the aim of investigating why self-control deterioration appears to occur over time and the factors that might modulate this. Specifically it assessed – based on prior research - whether glucose (Gailliot et al., 2007) and/or levels of intrinsic motivation - drawing on Beedie and Lane's (2012) resource allocation account and the shifting priorities account (Inzlicht & Schmeichel, 2012; Inzlicht & Schmeichel, 2016) - influence the extent to which a temporary deterioration in self-control performance occurs following prior exertion.

This was done by following the methodological procedures of prior investigations, and employing the sequential self-control depletion paradigm (Hagger et al., 2010) and incorporating measures of both blood glucose (glycaemic response and administration of glucose drinks) and intrinsic motivation (self-report and manipulation). The thesis consisted of seven experimental studies. To maintain consistency with the methodological procedures of prior investigations, all seven studies employed the sequential self-control depletion paradigm (Hagger et al., 2010); an initial self-control task was administered followed by a second subsequent measure of self-control. This paradigm was implemented under a number of different conditions or between different populations (see paper six; adults 18-80 years were recruited) in an attempt to examine the factors that modulate a temporary impairment in self-control performance following prior exertion (Evans, Boggero, Segerstrom, 2016).

Overall the seven experimental studies all demonstrated that it is too simplistic to state that applying self-control in an initial task, leads to a temporary impairment in subsequent self-control performance; other factors need to be considered and one in particular intrinsic motivation level, appears to play a significant role. More specific findings alluding to these modulating factors will now discussed. In addition, future research directions and limitations will be addressed.

Glucose

Glucose is a vital source of energy for the brain (Amiel, 1994) with highly effortful cognitive tasks relying on glucose (Scholey, Harper, & Kennedy, 2009). Given the wide ranging evidence on the relationship between glucose and sequential self-control task performance (Dang, 2016), we wanted to expand on these findings in an attempt to supplement the research that addresses whether glucose availability plays a direct role in self-control performance; more research was needed. Consequently four studies examined the moderating effects of glucose on sequential self-control task performance. Paper one administered a 25g glucose drink but in later studies – to maintain consistency with prior research – a 40g glucose drink (studies three and four) was administered. We also measured peripheral levels of blood glucose in all of these studies, which paper seven also implemented (but without glucose drink administration). In one of these studies we also assessed whether the amount of fasting prior to the study session moderated any glucose effects on self-control performance (paper four).

Overall across the series of studies in this thesis, no direct effects of blood glucose were observed; no significant reduction in blood glucose levels following the application of self-control were found nor did a glucose (25g or 40g) relative to placebo drink enhance performance in a subsequent self-control task following prior exertion. Fasting level also had no moderating effects; findings revealed no differences in any glucose effects between participants that fasted for two hours to those that fasted for four hours (paper four). Overall the findings in the thesis support more of the recent literature that blood glucose availability has no direct effect on self-control performance, namely across two sequential tasks (Dang, 2016; Molden et al., 2012; Sanders et al., 2012). The thesis therefore supplemented the existing literature; and failed to replicate prior glucose findings (e.g. Gailliot et al., 2007).

Individual differences in glucose regulation

An association was observed however between individual differences in glucose regulation – how effectively one processes glucose through the body (Lamport, Lawton, Mansfield & Dye, 2009) – and self-control ability. In paper three - filling a research gap - findings revealed that irrespective of the initial tasks completed, good glucose regulators performed better in the incongruent Stroop and antisaccade tasks; poorer glucose regulation displayed a weakened performance in self-control tasks in general. Thus there were no differences in terms of depletion effect but interesting in that glucose regulation affected self-control performance in general. This was not extended to working memory or the completion of more basic tasks; the congruent Stroop and prosaccade tasks.

This is consistent with Baumeister and Vohs's (2016) argument that research has robustly observed that when blood glucose levels are low, self-control appears to be weaker. For example the evidence fits consistently with observed associations between symptoms of diabetes mellitus and poor glucose tolerance and high levels of aggression, a characteristic associated with poor self-control (DeWall, Baumeister, Gailliot, & Maner, 2008; Baumeister & Vohs, 2016). This evidence suggests that glucose is somewhat linked to self-control ability but it does not directly fuel self-control as there is little evidence that glucose levels significantly deplete following prior exertion (Dang, 2016).

Motivation

Alternatively the evidence provided in this thesis suggested that motivation was a more powerful predictor of self-control performance following prior exertion. Specifically findings appeared to be more supportive of the resource allocation account of self-control (Beedie & Lane, 2012); it was not that resources were depleted following prior exertion; it is that resources were not allocated – with the allocation of resources being driven by how motivated one was - to the successful completion of the second task. Evidence provided in this thesis and more recent literature suggests that glucose does not directly fuel self-control ability (Dang, 2016); it is about how one allocates resources to effortful cognitive exertion (Beedie & Lane, 2012).

Studies one and three observed motivation played a significant role in sequential self-control task performance. Using a self-reported measure, intrinsic motivation was a stronger predictor of subsequent self-control performance in an anitisaccade task; those low than high in self-reported levels of motivation made more erroneous responses following the previous application of self-control in an incongruent Stroop task. Findings from paper two – in some of the smaller studies - tentatively observed this too.

Further, in paper five we manipulated self-awareness to observe whether the restorative effects of high self-awareness on self-control depletion that Alberts, Martijn, and De Vries (2011) had previously observed stemmed from a relationship between self-awareness and high motivation. In particular it was based around the idea that being more self-aware meant that one was more motivated to perform the task, as high self-awareness alerts one to their level of performance in a task, resulting in the motivated injection of energy into performing the task well (Wicklund, 1979). Results revealed a relationship between motivation, self-awareness and self-control performance; those that were self-aware or not primed with self-awareness but were high in intrinsic motivation performed better in a second task of self-control following prior exertion. Those primed with self-awareness tended to be more intrinsically motivated overall. This reflects previous findings and more recent models of self-control, which suggest that motivation may alleviate self-control depletion over time.

Paper six also observed that heightened motivation – particularly with increasing age – had a restorative effect on subsequent self-control performance following prior exertion in terms of a quicker Stroop response. We speculated that because cerebral blood flow (CBF: glucose metabolism) namely in the frontal brain areas, such as the prefrontal cortex decreases with age (Martin, Friston, Colebatch, Frackowiak, 1991), for older aged adults' cognitive exertion in tasks requires more effort and thus only when one is motivated will time and effort be applied to a task; thus if highly motivated, cognitive energy will be applied.

Moreover, as an extension to our previous findings on the relationship between motivation and self-control, paper seven manipulated motivation (by priming task interest and importance) and observed whether high motivation had a similar ameliorating effect on a temporary deficiency in self-control following prior exertion. Findings revealed that following initial self-control exertion, those primed with task interest (high motivation condition) made faster responses in the subsequent antisaccade task than those in the low motivation condition; this was not extended to those that completed the initial congruent Stroop task.

Findings from paper four somewhat fit less consistently with the resource allocation (Beedie & Lane, 2012) and motivational account however as intrinsic motivation was reported to overall - regardless of the initial task completed - predict erroneous response rate; those high in motivation committed less errors in the antisaccade task. Nevertheless we speculated that this might stem from the recruitment of a larger sized sample (N=120). Earlier studies had been criticised for their reliance on small samples arguing that the ego depletion effect was limited to these smaller samples (Carter et al., 2015), thus we addressed this by using a larger sized sample with more power. As this study only observed motivation to influence antisaccade performance irrespective of the initial task completed this has added to the literature tentatively supporting the idea that the ego depletion effect is restricted to smaller studies.

What are the physiological mechanisms responsible for the moderating effects of motivation on self-control?

Although the findings from the earlier studies in this thesis showed that motivation played a key role in sequential self-control performance it was only possible to speculate about the possible physiological mechanisms responsible for the restorative effects of motivation on self-control performance following prior exertion. Paper seven therefore explored the possible physiological mechanisms behind the allocation of resources to self-control performance when motivated. Research suggests a connection between dopamine activity and the motivation to engage in effortful tasks, and therefore dopamine levels were measured using eye blinks; a higher rate of blinks is indicative of higher dopamine activty (Dang, Xiao, Liu, Jiang, & Mao, 2016). Further, motivation might have induced an acute stress response, activating the sympathetic nervous system (SNS). Salivary alpha amylase (sAA) is considered a biomarker of SNS activity (Rohleder, Nater, Wolf, Ehlert & Kirschbaum, 2004; Nater & Rohleder, 2009). Findings revealed the high motivation group produced more blinks - which suggest higher dopamine activity (Karson, 1983) - and less sAA. We speculated based on previous research that low or more sustained levels of sAA when highly motivated might be linked to a reduction in stress as the task/situation matched ones' own goals (Schwab, Wolf, & Memmert, 2015). The evidence adds validity to ours and previous findings; motivation appeared to be paired with a physiological response.

Antisaccade task

An examination of the previous literature showed a lack of consistency in the way self-control had been defined and/or operationalised resulting in much dispute about the range of tasks used to assess why with continued exertion a temporary impairment in the ability to apply self-control occurs (Hagger et al., 2010; Reynolds & McCrea, 2016).

Drawing on this, the studies in this thesis incorporated a more objective measure of self-control - the antisaccade task (Hallett, 1978) - as a possible biomarker for the measurement of self-control. The antisacacde task is considered a purer and more objective measure as it requires the one modality of vision to process the information and provide a response. Prior tasks lacked this and relied on two modalities (Luna, Garver, Urban, Lazar, & Sweeney, 2004). Administering the task within such a design was relatively novel as to date and to the author's knowledge only one previous study (Brewer, Spillers, McMillan, & Unsworth, 2011) had used the antisaccade task as a measure of inhibition in a sequential self-control task paradigm.

Six out of the seven studies of this thesis employed the antisaccade task as a novel measure of self-control, with a specific focus on this being the dependent measure of self-control (with the exception of paper two, in which it was also employed as the initial depletion task). Overall the findings from the experimental studies within this thesis (studies one to five and seven) suggest that the antisaccade task can be successfully implemented into a sequential self-control task design and could be used in the future in studies on self-control. There was however some disparate findings in particular with the eye movement parameter used to measure level of self-control expended. The majority of studies reported an effect on antisaccade error rate with the exception of paper seven reporting an effect of motivation on antisaccade response time. However Carter et al (2015) reported that either parameter is acceptable as a measure of self-control; no conditions are in place stating that one is superior to the other.

Administration of identical self-control tasks vs. dissimilar tasks

Another research area this thesis addressed was whether the typical response of a temporary deterioration in self-control ability following prior exertion was unique to dissimilar tasks or whether it extended across identical tasks. The majority of previous research on self-control used different tasks as the initial and subsequent self-control tasks (Hagger et al., 2010); limited previous research involved identical task administration. Lange (2015) noted that it is not stated that resource depletion should be specific to solely dissimilar task administration; it should be wide ranging and applicable to the sequential administration of identical tasks. Thus paper two investigated whether depletion effects were unique to the sequential administration of dissimilar tasks or whether this would also extend to identical task completion (see chapter four). Findings illustrated that a temporary deterioration in self-control performance occurred when two identical tasks were sequentially completed. Findings for the studies that administered two dissimilar sequential tasks produced less consistent results. Additionally motivation influenced self-control performance in some instances with participants high in motivation performing a subsequent self-control task better following prior exertion than those low in motivation.

This thus addressed a research gap, supplementing the literature on self-control depletion and the conditions in which it is likely to occur, specifically with identical task administration. A limitation of this was on the employment of a relatively small sample size, which Gailliot et al's (2007) studies on glucose have previously been criticised for (Carter et al., 2015). Despite this the evidence is insightful and is a good basis for future research.

Highly effortful initial task completion: adaptation or greater vulnerability to depletion?

Another key question that this thesis assessed was whether a more cognitively demanding initial task – such as a dual task (self-control task paired with a working memory task) – would produce greater subsequent temporary impairment in task performance or an enhanced performance (paper two). This would also examine whether different executive functions tap similar processes and resources. If deterioration occurred this would suggest self-control and working memory are drawing on the same resources. Findings were however mixed, which arguably stem from the limited small sample size incorporated.

This was similarly examined in paper three with the administration of two initially cognitively effortful tasks - a working memory task followed by a self-control task. Findings suggested that working memory and inhibition tap into similar processes as performing the working memory task paired with basic congruent Stroop task led to a temporary deterioration in antisaccade performance for those low in motivation; more erroneous responses were made. Depletion effects thus extended to another executive function; working memory. Completing three cognitive tasks consecutively - working memory, incongruent Stroop and antisaccade tasks led to a better antisaccade performance – fewer errors - supporting the adaptation account (Converse & DeShon, 2009). Thus working memory and self-control could be argued to tap into similar processes and that adaptation is more like after completing three cognitively effortful tasks that rely on executive control processes.

Replicating previous findings to a wider age range of participants

Does age have a moderating effect on the extent that an initial self-control task adversely affects performance in a subsequent task of self-control? This was an important question that paper six examined. Exploring the relationship between age and self-control performance was lacking from the previous literature; predominately research had relied on the recruitment of younger aged adults, namely University students with few studies expanding the literature to older aged adults. Of the few studies that previously tapped into this, disparate results were observed; some replicating self-control depletion effects in older aged adults (Bray, Ginis & Woodgate, 2011), others not (Dahm, Neshat-Doost, Golden, Horn, Hagger & Dalgleish, 2011). Therefore paper six attempted to replicate an earlier study and employed two frequently used measures of self-control (Hagger et al., 2010) but widened recruitment to older as well as younger aged adults. Replication is a prominent issue in Psychology (Carter et al., 2015; Carter, & McCullough, 2014) and science in general, thus repeating an earlier study seemed appropriate here, particularly when attempting to extend the findings to older aged adults. We observed an interesting relationship between age and motivation on self-control performance over time. Motivation more powerfully predicted self-control performance following prior exertion and this occurred with increasing age; a stronger effect was observed in older aged adults. Thus addressing a research gap the findings from the study again pointed to the significance of accounting for motivation when examining the ability to apply self-control continually over time.

Limited beliefs about willpower

Job and colleagues (e.g. Job, Dweck, & Walton, 2010; Job, Walton, Bernecker, & Dweck, 2013; Miller, Walton, Dweck, Job, Trzesniewski, & McClure, 2012) suggested that one's belief about willpower capacity has an influential effect on level of self-control depletion experienced following initial self-control exertion. Due to the expanding literature on the possible moderating effects of limited willpower beliefs on self-control we incorporated an assessment of limited beliefs about self-control into two of the studies (studies four and seven) in this thesis. Both studies revealed no modulating effects of willpower beliefs on sequential self-control performance, thus challenging the earlier research by Job and colleagues (2010; 2013) that limited beliefs moderated the effect of initial self-control exertion on subsequent self-control performance.

Previous research examining the modulating effects of willpower beliefs on ego depletion appears to be relatively consistent; those that believe self-control was limited showed a temporary deterioration in performance in the second of two sequential self-control tasks. In this series of PhD studies we failed to observe this. We used the same questionnaire that had previously been used to assess the modulating effects of willpower beliefs on self-control (Job et al., 2010). One could speculate that the reason for these different results stemmed from the relatively more demanding experimental design in the studies that incorporated willpower belief measures compared to prior research. Specifically we incorporated other measures such as motivation and trait self-control, measured blood glucose levels and in some cases administered glucose drinks. Alternatively, it could be speculated that it is not that clear cut to state that believing willpower is limited leads to ego depletion; there are perhaps more factors involved, including motivation, which these series of PhD studies suggest. More research is needed however to explore this further.

Trait levels of self-control

The prior evidence on the moderating effects of trait levels of self-control on sequential self-control task performance produced mixed results (e.g. Dvorak & Simons, 2009; Freeman & Muraven, 2010; Imhoff, Schmidt, & Gerstenberg, 2013). Across five of the studies (not included in studies six and seven due to time constraints) Tangney, Baumeister and Boone's (2004) 35 item self-control scale was administered to participants to assess the potential moderating effects of individual differences in trait self-control on self-control performance across two (or more) concurrent tasks. With the exception of paper one, the studies in this thesis observed no moderating effects of trait self-control on level of performance in the subsequent self-control task. The lack of evidence might stem from the problems that exist with relying on self-reported measures (Podsakoff, 1986). We did however observe self-control correlated with glucose tolerance level (see paper three, chapter five) suggesting that those with high trait self-control have better glucose tolerance, pointing to a link between individual differences in self-control and one's ability to effectively process glucose in the body.

The association between individual differences in self-control and self-control performance over time has previously produced mixed results (Dvorak & Simons, 2009; Freeman & Muraven, 2010; Imhoff, et al., 2013). It might be more conducive in the future to examine the moderating effects of depletion sensitivity – how quickly one's self-control resources are diminished (Salmon, Adriaanse, Fennis, De Vet, & De Ridder, 2016) - on sequential self-control task performance. For example, evidence revealed an effect of depletion sensitivity but not of individual differences in self-control on food choices; the more vulnerable one was to resources being used (depletion sensitive) the more unhealthy snacks selected (Salmon et al., 2016). Thus individual differences in depletion sensitivity rather than trait levels of self-control might be a more delicate indication of individual differences to vulnerability to experiencing a temporary deterioration in self-control performance in a second task following prior exertion.

Future research

Overall this thesis tackled an ongoing and much debated area of research on why self-control appears to temporarily wane over time with continued exertion, specifically when faced with completing two sequential self-control tasks. The thesis has extended some earlier research, particularly on the potential role of motivation in successful self-control performance. Within the thesis – for each study/paper - ideas for future research have been discussed. Overall these are based around two specific themes. The first suggests that we could further manipulate motivation and assess the effect on self-control performance, and delve further into the physiological mechanisms behind this. Paper seven tentatively showed that dopamine activity and levels of sAA might play a role in this, which based on the research findings, is worth exploring further in the future. Secondly the findings we observed on the relationship between glucose tolerance level and self-control ability could be extended, particularly by recruiting a much larger sample size to increase power to observe whether our findings could be replicated. Further, this thesis provided an insight into self-control performance during identical task administration. Again this insight was based on a relatively small sample size, particularly when we consider the discussions that exist about ego depletion and it being limited to smaller samples (Carter et al., 2015). It therefore would be beneficial to further administer identical self-control tasks in a sequential task paradigm with a larger pool of participants along with measuring and manipulating motivation to assess this further.

Limitations

The methodological weaknesses of each of the experimental studies were discussed where appropriate in the relevant discussion sections of each chapter. However some of the issues that we feel should be highlighted, are raised here.

For example one could question the type of parameter that was used to measure self-control performance. In general, consistency was observed across studies for the parameter we used to measure self-control performance; the studies examined both error rate and response time. Consistently across the studies we observed error rate produced the most differences based on initial task performance and motivation level [studies 1, 2, 3, 4, 5]; no differences were observed for response time. However there were two exceptions; both studies six and seven observed response time performance differences. Carter et al (2015) however argued that there is no evidence to suggest that one performance parameter should be favoured over another when measuring self-control ability. One could speculate that it might depend on the task being analysed. For the antisaccade task, differences might appear more strongly for the parameter error rate but for the Stroop (see paper six) task differences in response time based on the condition and motivation level, might be more obvious.

Studies in this thesis could be criticised for focusing too much on self-control failure. For example research by Gillebaart and Ridder (2015) suggested that most of the literature, which has examined self-control performance over time, has specifically focused on when self-control fails with little attention being directed towards self-control success i.e. what is it that makes someone able to continually apply self-control in two sequential self-control tasks. Thus future research on self-control should be directed towards this. However we wanted to expand the existing literature which particularly has focused on self-control failure. In addition one could argue that in a way the findings provided information and testable hypotheses about self-control success through the observations that if one is highly motivated on an intrinsic level i.e. a task is perceived to be interesting and enjoyable, self-control is successfully maintained.

Moreover the duration of the initial tasks that prior studies used to exhaust self-control has been criticised; longer tasks should be employed to foster the likelihood of self-control depletion (Maranges et al., 2016; Hagger et al., 2010). Despite this, the initial tasks employed in the studies within this thesis were consistent with a large proportion of previous research on self-control. The task duration of the initial tasks were appropriate and encouraged a comparison with prior investigations. Future studies should however account for this and compare initial tasks of differing lengths to observe whether a temporary deterioration in self-control performance in a second task differs depending on the length of time that self-control is initially expended.

Conclusions

In summary, this thesis explored a heavily debated topic and addressed the potential factors involved in why self-control performance appears to temporarily wane over time across sequential tasks. It has attempted to address some of the important research gaps and added to an area of research that is heavily disputed and significant in Psychology. In particular this thesis has provided support for more of the recent findings and theories, which point to the role of motivation rather than a direct role of glucose availability in self-control performance.

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