A Social Neuroscience Perspective on Physical Activity

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The objective of this investigation was to examine the cognitive characteristics of individuals who demonstrate successful and unsuccessful self-regulation of physical activity behavior. In Study 1, participants articulated 1-week intentions for physical activity and wore a triaxial accelerometer over the subsequent 7 days. Among those who were motivated to increase their physical activity, those who were most and least successful were administered an IQ test. In Study 2, a second sample of participants completed the same protocol and a smaller subset of matched participants attended a functional imaging (fMRI) session. In Study 1, successful self-regulators (SSRs) scored significantly higher than unsuccessful self-regulators (USRs) on a test of general cognitive ability, and this difference could not be accounted for by favorability of attitudes toward physical activity or conscientiousness. In Study 2, the IQ effect was replicated, with SSRs showing a full standard deviation advantage over USRs. In the imaging protocol, USRs showed heavier recruitment of cognitive resources relative to SSRs in the anterior cingulate and orbitofrontal cortex during performance of a Stroop task; SSRs showed heavier recruitment in the right dorsolateral prefrontal cortex.

Keywords: health behavior, self-regulation, executive function, intelligence, exercise

Most explanatory models of health behavior are constructed from a rational perspective. In such models, health protective behaviors (e.g., exercising regularly, eating healthy foods) and health risk behaviors (e.g., smoking cigarettes, engaging in unprotected sexual intercourse) are thought to be reflections of choices made in the context of an active decision-making process. The theory of reasoned action (TRA; Ajzen & Fishbein, 1980), for example, suggests that motivation to perform a health behavior is partially determined by an estimation of the anticipated outcomes of performance of the behavior in question coupled with the value attached to

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such anticipated outcomes. All influences on behavior are thought to be channeled through intention, such that behavioral intention is necessary and sufficient to predict and explain behavioral performance. In light of misgivings about the exclusivity of intention inherent in the original model, a subsequent revision of the TRA—the theory of planned behavior (TPB; Ajzen & Madden, 1986)—was introduced. The TPB incorporated the notion of “perceived behavioral control” to account for behaviors that were ostensibly not completely under the control of the individual. Perceived behavioral control was thought to influence intentions to perform a behavior, as well as the performance of the behavior itself. Neither the TRA nor the TPB, however, propose any moderators of the intention–behavior link: According to the TRA and the TPB, factors within and outside the individual affect intention and perceived control affects behavior, but no additional factors are thought to influence the ease with which individuals translate intentions regarding health behaviors into performance of health behaviors. Thus, a high degree of intention–behavior continuity is assumed in both models, despite mounting evidence that the relation between intention and behavior is neither uniform nor universal (Webb & Sheeran, 2006). This suggests the need for a rethinking of some of our current theories of health behavior.

Intention–Behavior Continuity Revisited

With intention–behavior continuity as a core assumption, an exclusive focus on the determinants of the intention itself is perfectly defensible. Not surprisingly, the rational approach has a long and rich tradition in the social sciences (Edwards, 1954), and in health promotion in particular (Sutton, 1998, 2005). It could be argued that such approaches would be most defensible when: 1) the behavior in question is discrete rather than repetitive, 2) the behavior is fully under the control of the individual, and 3) costs and benefits of the behavior occur at the same point in time allowing for equal temporal weighting. It could be further argued that health-protective behaviors like physical activity do not meet the first two criteria, and likely do not meet the third (Hall & Fong, 2007). Indeed, many health behaviors are not only recurrent, but are also characterized by a temporal dispersion of behavioral contingencies; that is, costs and benefits occur within entirely different time frames. Most of the benefits of health-protective behaviors (e.g., improved health status, improved appearance) accrue only after repeated performance over time, whereas costs (e.g., inconvenience, discomfort) are much more immediate. For health risk behaviors, the reverse is true: benefits (e.g., euphoria, stress reduction) occur at the time of action, whereas costs (e.g., development of illness, mortality) occur only after repeated performance over extended periods of time. Accordingly, on a conceptual level, it has been argued that the temporal nuances of health behaviors necessitate a self-regulatory perspective rather than a simple decision-making framework (Baumeister, Heatherton, & Tice, 1994; Carver & Scheier, 1982; Hall & Fong, 2007; Schwarzer, 2001).

There is substantial empirical justification for a reconceptualizing of health behavior as well. For example, Webb and Sheeran (2006) recently reviewed a large body of experimental literature on intention–behavior relationships. They concluded that although a wealth of accumulated evidence suggests that intention usually accounts for a moderate amount of variance in behavior, the actual proportion
of variance accounted for is overestimated by nonexperimental designs, and the intention–behavior relationship is frequently moderated by other variables. With respect to the latter, there is specific evidence that executive abilities represent one such moderator, at least for health-protective behaviors like physical activity and dietary choice (Hall, Fong, Epp, & Elias, 2008).

The Neurobiology of Self-Regulation

Behavioral self-regulation is commonly described in terms of the cognitive processes that facilitate it (Bandura, 1997). Such self-regulatory activities are fundamentally dependent on the operation of structures in the frontal regions of the brain, particularly the prefrontal cortex (PFC) (Fuster, 1999; Gehring & Knight, 2000; Paus, 2001). Often referred to as “executive functions” (Fuster, 1999; Norman & Shallice, 1980), these reflect top-down cognitive processes that serve the purpose of regulating behavior in line with a goal. The “executive function” construct is multidimensional (Miyake et al., 2000), referring to a variety of cognitive operations that enable such goal-directed behavior, including working memory, attention, and the ability to suspend prepotent (i.e., habitual or default) responses to cues. To the extent that health-protective behaviors, like physical activity, require disengagement from immediate cues that might impel nonperformance (i.e., inconvenience, discomfort), in favor of goal-directed actions with favorable longer-term outcomes (i.e., improved appearance, stress management, reduced risk of illness), executive abilities may be important determinants of health behavior performance.

The notion that individual differences in neuroanatomy and cognitive ability may be implicated in health and longevity has been supported by several recent epidemiological studies. In a seminal study, Whalley and Deary (2001) found that IQ was prospectively associated with all-cause mortality in an age cohort of 2,792 children from Aberdeen, Scotland, who participated in the Scottish Mental Survey in 1932. Children with a 1 standard deviation disadvantage in IQ were 21% less likely, and those with a 2 standard deviation disadvantage were 37% less likely, to live to age 76 than the comparison group. This effect held for both genders analyzed separately and remained strong after statistically controlling for an indicator of socioeconomic status. In a second large-scale prospective study, Osler and colleagues (Osler et al., 2003) found that IQ measured at age 12 in a sample of 7,493 Danish men born in 1953 was inversely associated with all-cause mortality at 50-year followup after controlling for social class and birth weight, and this effect seemed particularly pronounced for mortality occurring in the 35–49 age range. To date, the IQ–mortality association has been observed using multiple IQ assessment strategies and in most cases remains strong after controlling for socioeconomic status and education (Deary, Whalley, & Starr, 2003; Deary, Whiteman, Starr, Whalley, & Fox, 2004; Hart et al., 2003; Osler et al., 2003).

Despite strong evidence in support of the IQ-mortality link, the mechanism by which cognitive function affects mortality remains unclear. To date explanations fall into three primary categories: 1) IQ as an early indicator of the biological integrity of the human body, 2) IQ as a harbinger of advantageous social conditions (e.g., safer work environments, better access to healthcare services) that in turn influence mortality rates, and 3) IQ as a determinant of health-protective behavior patterns over the lifespan (e.g., smoking cessation, physical activity, healthy diet). In support of
the bodily integrity hypothesis, Deary and Der (2005) demonstrated that although IQ was predictive of mortality in the Twenty-07 Study, the association disappears when controlling for performance on a simple reaction time task. The association between reaction time and mortality, however, remains strong after controlling for the confounding effects of social class, smoking, and IQ, suggesting that raw processing speed—as a proxy for bodily integrity—may explain (statistically) the observed association between IQ and mortality. Other studies have demonstrated that social class accounts for some of the association between IQ and mortality, providing evidence in support of the socioeconomic hypothesis (Hart et al., 2003; Osler et al., 2003).

A significant body of indirect evidence has also begun to accumulate in support of the health behavior hypothesis. Additional analyses of the Scottish Mental Survey have revealed an inverse association between IQ and the early development of cardiovascular diseases (Hart et al., 2003; Hart et al., 2004) and lung cancer (Deary et al., 2003). Interestingly, both cardiovascular disease and lung cancer are at least partially preventable through the adoption of consistent health-protective behavior patterns over the lifespan. Hart et al. (2005) also found that those with high IQ were just as likely as those with low IQ to start smoking in the 1930s and 1940s, but were more likely to quit in later decades when the dangers about smoking became well known. Recent smaller-scale studies have also provided evidence that executive ability is uniquely associated with health behavior patterns in healthy, community-dwelling adults (Hall, Elias, & Crossley, 2006) and that executive ability moderates the association between intention and behavior for both physical activity and healthy dietary choice (Hall et al., 2008).

In summary, there is preliminary evidence to suggest that individual differences in cognitive ability are associated with longevity, and some of the data hint that health behavior performance could play a mediating role. Moreover, a conceptual argument could be made that because of the high self-regulatory demands of health-protective behaviors, higher intention–behavior continuity in this domain may be associated with especially high levels of general cognitive ability, and executive ability in particular. As such, differences in cognitive function and associated neuroanatomical function may be observable between those who successfully regulate health behavior in line with intentions compared with those who do not. This may be especially true with respect to physical activity behavior, which inherently involves a number of subtle barriers to performance at the time of action (Hall & Fong, 2007).

The Present Study

In executing the current studies, we sought to answer two questions: (1) “are those who successfully self-regulate their health-protective behavior in accordance with their intentions characterized by higher levels of general cognitive ability than those who are less successful (Study 1)?,” and (2) “are there functional neuroanatomic differences between successful and unsuccessful self-regulators in the areas of the brain normally associated with self-regulatory abilities (Study 2)?” To answer these questions we first conducted a prospective behavioral study (Study 1) designed to test the hypothesis that successful self-regulators will have higher general cognitive ability (operationalized as IQ) than unsuccessful self-regulators.
We then used an identical behavioral paradigm to select a smaller group of individuals for participation in a functional imaging study, to replicate the original IQ effect and test the hypothesis that successful self-regulators will be characterized by coactivation of the anterior cingulate cortex (ACC) and orbitofrontal cortex (OFC; Study 2). Given that the ACC and OFC are activated in response to cognitive conflict, which in turn depends largely on task difficulty, it was expected that USRs will show stronger activation in these areas relative to the SSR group because of their need to recruit more cognitive resources for task completion. Moreover, effective engagement of higher attentional structures (i.e., the dorsolateral prefrontal cortex; DLPFC) should reduce the processing load on the ACC, resulting in reduced activation among those who are more effective in dealing with the demands induced by cognitive tasks that tend to tap frontal function. Such hypotheses would also be consistent with earlier empirical findings showing reduced activation in the ACC among young adults with high cognitive abilities during performance of demanding cognitive tasks (Rypma & D’Esposito, 2000).

Study 1

Methods

Participants

A sample of 124 undergraduates (see Table 1) articulated behavioral intentions for physical activity in initial laboratory session, and were fitted with a triaxial accelerometer and given instructions as to its use.

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>SD</th>
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<tbody>
<tr>
<td>Age (years)</td>
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<table>
<thead>
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<th>Ethnicity</th>
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<td>12.1%</td>
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<tr>
<td>African American</td>
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<tr>
<td>Caucasian</td>
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<tr>
<td>Middle Eastern</td>
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<tr>
<td>Other</td>
<td>2.4%</td>
</tr>
<tr>
<td>Missing</td>
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</tr>
</tbody>
</table>

Note. N = 124.
Procedures
At Session 1, after informed consent was obtained, participants completed self-report measures of intentions for physical activity over the next week, and a self-report measure of physical activity over the past week. Participants also completed a number of other questionnaires described below. At the end of the session, participants were given an RT3 triaxial accelerometer, which was to be worn on the hip. Participants wore the accelerometer continuously except during sleep hours or when in contact with water (e.g., showering, bathing) for the next 7 days. On the seventh day, participants returned to the laboratory, their accelerometer data were downloaded, and they were debriefed. In a separate session, selected participants were invited back to the laboratory for additional IQ and personality testing. This protocol was reviewed by and received ethical clearance from the relevant institutional review boards.

Measures

**Attitudes.** Attitudes toward physical activity were assessed via a semantic differential scale, wherein participants responded to the sentence stem, “For me to participate in regular vigorous or moderate physical activity or exercise would be . . .” using a response scale consisting of 10 polar opposite adjective pairs (e.g., pleasant/unpleasant, enjoyable/unenjoyable). Participants placed a check mark along a continuum of seven blank spaces between each pair of adjectives to represent their assessment of physical activity for each bipolar dimension. Responses were then summed to form a global measure of attitudes toward physical activity.

**Behavioral Intentions.** Behavioral intentions for physical activity were assessed at baseline using a rewording of the International Physical Activity Questionnaire (IPAQ) for vigorous and moderate intensity physical activities. Wording was adjusted so that the measure assessed hours of intended physical activity (to the nearest half hour) over the upcoming 7 days.

**Conscientiousness.** Individual differences in Conscientiousness were assessed using items extracted from the Big Five Mini-Marker Scale developed by Saucier (1994). This scale has been normed and validated for use with the young adult population.

**IQ Assessments.** In a separate session, participants were administered the Wechsler Abbreviated Scale of Intelligence (WASI) by a trained doctoral student in clinical psychology. The WASI is an abbreviated version of the WAIS tests, which are considered to be the gold standard of IQ assessment tests. Correlations between the WASI and the WAIS-III full-scale scores are .92, and other indices of WASI reliability and validity are comparable to that of other Wechsler tests (Psychological Corp.; Stano, 2004). Both the assessor and the participants were blind to group membership.

**Past Behavior.** Past behavior was assessed at baseline using a slightly reworded version of the vigorous and moderate intensity activity subscales of the IPAQ—short form physical activity self-report scale. This is a self-report scale that has undergone
extensive validation and demonstrates good test–retest reliability (Craig et al., 2003). The present version asked respondents to indicate vigorous and moderate physical activity to the nearest half hour according to a predefined intensity criterion.

**Physical Activity Behavior.** Physical activity behavior was assessed by a hip-mounted triaxial accelerometer, worn over the course of the 7-day follow-up interval. The accelerometer model used was the RT3 triaxial accelerometer (StayHealthy Inc.), which measures acceleration simultaneously along the vertical (x), anteroposterior (y), and mediolateral (z) axes. Triaxial accelerometers are considered reliable and valid measures of physical activity because they sidestep some of the difficulties associated with self-reported activity; the RT3 has undergone extensive validation and demonstrated good reliability and validity (Rowlands, Thomas, Eston, & Topping, 2004; Rowlands, Stone, & Eston, 2007). Average activity counts per day, summed across all three planes of motion \((x^2 + y^2 + z^2)^{0.5}\) constituted the unit of measurement (i.e., vector magnitude). Only participants who wore the accelerometer for five or more days out of seven were included in the analysis to ensure stable estimates of daily activity.

**Statistical Analyses and Group Selection**

Following completion of the behavioral phase of the study, 117 participants agreed to be contacted for subsequent IQ and personality testing. Of these, 5 did not have usable RT3 data (either due to equipment failure or noncompliance) and were excluded, leaving 112 participants available for subsequent selection procedures. Using this sample, the data set was stratified such that only participants in the top 50% \((n = 56)\) in terms of positive discrepancy between past behavior and baseline intentions for physical activity were selected to ensure that all participants were motivated to increase physical activity from baseline level. Out of this selected sample, the sample was further stratified into thirds based on magnitude of achieved increase in behavior from baseline over the course of the week, such that the top third included individuals who demonstrated the largest increases from baseline, whereas those in the bottom third showed no change or decreases from baseline. These procedures resulted in the identification of 19 successful self-regulators (SSRs) and 17 unsuccessful self-regulators (USRs) who underwent additional personality and cognitive testing (one USR could not be located for follow-up). Two participants from each group were excluded because they indicated that English was not their first language, thereby affecting the validity of the WASI results. This left 17 SSR participants and 15 USR participants, and subsequent categorical group comparisons are based on these participant groups (Table 2). The testing session included the administration of the WASI by trained clinical psychology doctoral students in a separately scheduled testing session, and completion of self-report measures of attitudes toward physical activity and conscientiousness. Both participants and those administering the assessments were blind to group membership. Subsequently, ANCOVA procedures were used to examine whether the two groups differed on IQ after covarying on demographic variables (age, gender, ethnicity).
Results and Discussion

Characteristics of successful and unsuccessful self-regulators are presented in Table 2. The groups did not differ significantly on any baseline demographic variables or BMI. In addition, as indicated in Table 3, the two groups also did not differ significantly in initial level of intended increase in PA from baseline. As expected, however, the SSRs engaged in significantly more physical activity over the follow-up interval than the USRs. Importantly, we found that successful self-regulators (M = 110.06, SD = 8.09) were characterized by higher levels of general cognitive function than unsuccessful self-regulators (M = 105.43, SD = 7.19) and this difference is statistically significant after controlling for age, gender, ethnicity, and education level, F(1, 30) = 5.29, p = .030, d = 0.60. In a second model including conscientiousness as a covariate, the main effect of group remained statistically significant, F(1, 30) = 5.01, p = .035. Successful self-regulators (M = 6.02, SD = 1.03) did not differ from unsuccessful self-regulators (M = 5.69, SD = 0.88) in terms of attitudes toward physical activity (t(27.62) = .925, p = .363) or in terms of dispositional conscientiousness: M = 5.74, SD = 1.27, for successful self-regulators; M = 6.12, SD = 0.85, for unsuccessful self-regulators (t(27.93) = −.997, p = .328).

These results provide initial support for the contention that cognitive ability is associated with self-regulatory success and failure, and suggest that differences between the two groups are not reflective of differences in attitudes toward physical activity, or differences in personality dimensions often implicated in health behavior tendencies (Bogg & Roberts, 2004).

In Study 2, we sought to examine the replicability of this effect, and to pinpoint the functional neuroanatomical correlates of self-regulatory success/failure.

Table 2  Study 1 Demographic Variables by Self-Regulation Group

<table>
<thead>
<tr>
<th></th>
<th>SSR Group (n = 17)</th>
<th>USR Group (n = 15)</th>
<th>Total (N = 32)</th>
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<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
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<tr>
<td>Male</td>
<td>11.8%</td>
<td>Male</td>
<td>13.3%</td>
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<td>Female</td>
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<td>86.7%</td>
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<tr>
<td>Ethnicity</td>
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<td></td>
<td></td>
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<tr>
<td>Aboriginal</td>
<td>17.6%</td>
<td>Aboriginal</td>
<td>6.7%</td>
</tr>
<tr>
<td>Asian</td>
<td>11.8%</td>
<td>Asian</td>
<td>0%</td>
</tr>
<tr>
<td>Caucasian</td>
<td>70.6%</td>
<td>Caucasian</td>
<td>6.7%</td>
</tr>
<tr>
<td>Other</td>
<td>0%</td>
<td>Other</td>
<td>6.7%</td>
</tr>
<tr>
<td>Age (years)</td>
<td>18.47</td>
<td>18.87</td>
<td>18.66</td>
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<td>Height (inches)</td>
<td>66.12</td>
<td>66.53</td>
<td>66.31</td>
</tr>
<tr>
<td>Weight</td>
<td>137.71</td>
<td>132.67</td>
<td>135.34</td>
</tr>
<tr>
<td>BMI</td>
<td>22.06</td>
<td>21.19</td>
<td>21.65</td>
</tr>
</tbody>
</table>

Note. SSR = successful self-regulator; USR = unsuccessful self-regulator.
Study 2

Methods

Behavioral Phase Procedure

A sample of 64 young adults (Table 4) completed the behavioral phase of a related study of intention–behavior relations (Hall et al., 2008), wherein they attended two laboratory sessions spaced 1 week apart. Again participants wore a triaxial accelerometer during waking hours with the exception of times when they were in contact with water and attended a second laboratory session after 7 days. At this point, their physical activity data were downloaded and they were debriefed. Individuals were again classified as successful and unsuccessful self-regulators as per the procedures used in Study 1. Two groups of four participants from each group matched on age, gender, and ethnicity participated in the imaging phase and subsequent IQ testing.

Imaging Phase Procedure

Those selected from the behavioral phase of the study were invited to participate in the imaging phase. A total of 58 participants (90.6%) agreed to be contacted for the imaging phase of the study. Two participants (3.1%) did not have accelerometer data, and three (4.7%) declined to participate when contacted after selection. A total of 53 (82.8%) of these had usable data for the final selection procedure.

fMRI Assessments. During the separate imaging session, each participant underwent informed consent again for the imaging portion of the study and was briefed on the operation of the scanner and the mouse. A practice session in a “mock” MRI was conducted using dummy tasks before the test to familiarize the participants with the apparatus and procedure. In the actual imaging session within the fMRI environment (1.5-T Siemens Symphony Magnetom imager), we administered a Stroop task wherein 36 incongruent color–word pairs were presented.

Table 3 Study 1 Physical Activity and Intention Variables for SSR (n = 17) and USR (n = 15) Groups

<table>
<thead>
<tr>
<th></th>
<th>Intentions to Increase PA</th>
<th>PA behavior (RT3)</th>
<th>Self-regulatory success index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSRs (n = 17)</td>
<td>1.26</td>
<td>255,746.00</td>
<td>1.12</td>
</tr>
<tr>
<td>USRs (n = 15)</td>
<td>1.57</td>
<td>165,146.80</td>
<td>−0.99</td>
</tr>
<tr>
<td>F-statistic</td>
<td>0.42</td>
<td>11.17</td>
<td>66.77</td>
</tr>
<tr>
<td>p value</td>
<td>.520</td>
<td>.002</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

*Note.* Intentions represents intended change from baseline physical activity (moderate and vigorous intensity combined); RT3 counts are expressed in vector magnitude units ($x^2 + y^2 + z^2)^{0.5}$ per day, averaged across the 7 days of the follow-up interval; self-regulatory success coefficients represent degree of increase in PA behavior relative to baseline expressed in $z$-scores. SSR = successful self-regulator; USR = unsuccessful self-regulator.
via a data projector onto a view screen against the window of the MRI suite, and the participants were instructed to silently name the color of the print as quickly as possible after it was presented. Two additional tasks were presented in counterbalanced order with the Stroop: the Tower of Hanoi task and a Go–NoGo task. However, owing to motion artifacts—presumably stemming from the selective use of the handheld mouse for response generation in these tasks—neither task yielded interpretable images for subsequent analyses. As such, subsequent image analyses were based on activation elicited by the Stroop task only.

To record the blood oxygenation level dependent (BOLD) signal, 77 volumes of 12 slice axial images were acquired with a repetition time, TR, of 3,700 ms, including a 1,850-ms gap of no image acquisition, using a gradient echo, single-shot echo planar imaging (EPI) sequence with fat saturation, an echo time TE of 55 ms, and a flip angle of 90°. T₁-weighted high-resolution spin-echo anatomical images (TR = 400 ms, TE = 12 ms, 256 × 256 acquisition/reconstruction matrix) were acquired in axial, sagittal, and coronal planes for the purpose of overlaying the activation maps and for defining a subsequent Talairach transformation. The position and thickness of the T₁ axial images matched the EPI images. The EPI slice thickness was 8 mm with 10 mm between slice center lines, the field of view was 250 mm × 250 mm, acquisition matrix was 64 × 64, and the data were Fourier reconstructed to 128 × 128 pixels. The first five EPI volumes were used for stabilizing the MRI signal (and were discarded). These volumes were followed by six blocks of six stimulus presentations, each of which were 12 volumes (7.4 s) in length (the first six volumes in each block were in sync with presentations of the stimulus, and the remaining volumes were “rest”). The fourth-most inferior slice was centered on the posterior commissure and oriented in the axial plane. The activation maps were computed

<table>
<thead>
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<th>Table 4 Study 2 Participant Demographics for the Behavioral Phase</th>
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<td><strong>M</strong></td>
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</tr>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Height (inches)</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>

**Gender**
- Male | 25.0%
- Female | 73.4%
- Missing | 1.6%

**Ethnicity**
- Aboriginal | 3.1%
- Asian | 12.5%
- Caucasian | 75.5%
- Middle Eastern | 1.6%
- Other | 6.3%
- Missing | 1.6%

Note: N = 64.
using a general linear model that corrected for linear baseline drift and produced a parametric estimate for the mean BOLD time course over the six blocks. A correlation statistic, $\eta$, was computed that represented the goodness of fit of the mean BOLD function to the observed BOLD data in terms of variance accounted for in the data by the mean response. This method of fMRI data analysis is described by Sarty and Borowsky (2005) and was implemented using locally written software. Pixels with a resulting correlation coefficient $\eta > 0.65$ and a maximum intensity change in the mean BOLD function of more than 5% of the maximum detected BOLD amplitude were considered activated. Confirmation of no false activations in regions of interest was achieved by visually examining the pixel signal time course to verify that it represented a smoothly varying hemodynamic response. Interpolated activation maps for each participant were produced at a voxel resolution of 1 mm$^3$ and then transformed into Talairach coordinates with the AFNI software package (Cox, 1996). The individual Talairached maps were then smoothed, using a within slice plane 3.91 mm FWHM Gaussian kernel, and the BOLD amplitudes averaged across individuals in each group. Using a between-subject extension of the method for separating unique from shared BOLD activation (Borowsky et al., 2005), a one-sample $t$ test ($\alpha = .05$, one-tailed) was used to identify significant activation in the two averaged group maps and the resulting positive maps were designated $A$ and $B$. Unique activations for each group were then identified by computing $(A - B)(1 - C^A_C^B)$, where $C^A$ and $C^B$ are indicator (on/off) functions for $A$ or $B$ activation.

Individuals conducting the image analyses (AH and RB) were blind to group membership of individual participants.

**Results and Discussion**

Demographics for the matched imaging sample are presented in Table 5. Significant differences in general cognitive function were evident between successful and unsuccessful self-regulators selected for the imaging protocol. Normatively, USRs ($n = 4$) fell in the “average” range ($M = 106.25, SD = 7.97$), whereas matched SSRs ($n = 4$) fell in the “superior” range ($M = 122.50, SD = 8.85$), or 22.5 IQ points above the theoretical population mean of 100. Almost no overlap in the range of IQ scores of the two groups was evident, and the observed difference in mean IQ scores between SSRs and USRs was statistically significant, even with this small sample size, $F(1, 6) = 7.44, p = .034; d = 1.93$. Mean T-scores for both groups on WASI subscales are presented in Figure 1. As hypothesized, clear group differences between SSRs and USRs were also observable in functional activation in the a priori regions of interest during in-scanner performance of the Stroop task; these are presented graphically in Figure 2. As can be seen in the hypothesized region of interest, USRs show significantly higher degree of activation in an area corresponding with the OFC and in the ACC relative to SSRs. An additional significant group contrast appears in the right DLPFC suggesting stronger activation of this higher structure in the SSR group relative to the USR group; this is consistent with the notion that reduced ACC activation in the SSR group may reflect decreased load on the conflict monitoring system from effective engagement of higher attentional structures during task completion.
Past research has demonstrated that induction of cardiovascular fitness through more vigorous forms of physical activity can selectively induce enhanced frontal function (e.g., Colcombe et al., 2004), and therefore we considered it important to assess this before the imaging procedure. Individuals in the two groups did not report significantly different levels of vigorous physical activity, $F(1, 6) = .369$, $p = .566$, or number of days engaged in cardiovascular physical activity, $F(1, 6) = 1.42$, $p = .278$, in the 7 days immediately before the scan.

Overall, our imaging findings reveal heavier recruitment of cognitive resources in the ACC and OFC areas among USRs, indicating more activation of error detection and deliberative processes in response to the cognitive challenge presented by the Stroop task. Those in the SSR group, however, show relatively more effective engagement of high-level executive attentional/inhibitory networks (i.e., right DLPFC). Coactivation of the ACC and OFC is common, and some have suggested that they represent a coherent system involved in behavioral correction; right DLPFC activation has been shown to modulate engagement of top-down attentional/inhibitory processes during performance of the Stroop task specifically (Vanderhasselt, De Raedt, Baekn, Layman, Clerinx, et al., 2007). Our findings are therefore consistent with the contention that prefrontal structures globally assist in the enactment of goal-directed behavior and could fulfill a facilitating function with respect to behaviors that require negotiation of cognitive conflict (Carter et al., 2000; Ito, Stuphorn, Brown, & Schall, 2003; MacDonald, Cohen, Stenger, & Carter, 2000; Osler et al., 2003; Paus, Koski, Caramanos, & Westbury, 1998; Paus, Petrides, Evans, & Meyer, 1993).
Figure 2 — The modular regions of activation unique to unsuccessful self-regulators (USRs; medium to light gray) versus successful self-regulators (SSRs; black to hatched), overlaid on the AFNI 3-D anatomical brain (individual threshold $\eta = .65, p < .001; t(7) = 2.201, p < .032$). Arrows point toward the face. The lateral-view maps (top) are overlaid on a 90% anatomical brain (i.e., 10% stripped away to enhance visualization; see Borowsky et al., 2005). The ventral-view (middle) and coronal section maps (bottom) are overlaid on a 100% anatomical brain. The regions of interest—corresponding with the OFC and the ACC—are indicated by squares. Original color image available upon request from first author.

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<th>Table 5 Imaging Sample Demographics</th>
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General Discussion

Our findings support the contention that successful self-regulators and unsuccessful self-regulators are characterized by differences in overall IQ, and in functional neuroanatomy of the prefrontal cortex. Those who showed higher self-regulatory success over a week for physical activity showed differential activation in the PFC during a simple Stroop task designed to elicit mild cognitive conflict, and scored significantly higher on a standardized IQ test than those who showed lower self-regulatory success. These findings suggest that those individuals who effectively translate behavioral intention into actual behavior may be somewhat unique in terms of general cognitive ability, and frontal lobe functioning in particular. Though not definitive, these findings do provide support for the notion that individual differences in cognitive ability may be associated with self-regulatory abilities in the domain of health behavior, which in turn could have implications for longevity if aggregated over the course of many years or decades.

These findings may give us a glimpse into the neurobiology of people who experience self-regulation as highly effortful and draining of personal resources. If groups differ along these functional neuroanatomical lines for a single task, the effect could be pronounced when aggregating over the behavioral challenges facing people who require ongoing self-regulation to maintain health status in a world that largely pulls for unhealthy behaviors as the default. Our findings converge with the existing literature on adherence to behavioral intentions in the health domain. It is clear that relatively few members of the population are able to realize their physical activity, dietary, and smoking cessation aspirations (Curry & McBride, 1994; Dansinger, Gleason, Griffith, Selker, & Schaefer, 2005; Dishman, 1991). Behaviorally, then, the average adult is a poor self-regulator with respect to health-protective behavior. Our unsuccessful self-regulators are, in this respect, strictly average in their ability to translate intention into actual behavior sustained over time (i.e., not very good). Our unsuccessful self-regulators are also average in terms of general cognitive function, as their IQ test scores fell normatively in the average range in both studies.

Some limitations exist with respect to the interpretation of these findings in isolation. Because we do not have accuracy scores for the Stroop task, we cannot definitively rule out the possibility that differential activation is due to poor performance on the Stroop task (and awareness of that poor performance) by the participant. In addition, there was no experimental manipulation of self-regulation or cognitive ability, and therefore statements regarding the causal primacy of the PFC for driving intentional behavior are speculative, although supported by converging evidence from past research (Paus, 2001). Finally, the size (Study 2) and unknown representativeness of the sample (Studies 1 and 2) constitute potential limitations. With respect to the former, the sample size in the imaging phase of Study 2—though typical of imaging studies—would be considered small for comparisons of group differences in IQ. The between-group differences that do emerge are, however, very strong as evidenced by the large effect size reported. Thus statistical significance is achieved despite the small sample size (not because of it). It is also important to note that between-group IQ differences were observed in both Studies 1 and 2. Nonetheless, confidence regarding generalizability of the IQ effect would be increased if these findings were to be replicated in a larger community-based
sample with greater age variability. Finally, the follow-up interval in this study was brief, and it is unknown to what extent longer follow-ups would yield the same findings. Given the especially small sample size of the imaging study (i.e., four participants per group) these findings in particular should be replicated before firm conclusions are drawn.

Strengths of these studies include the use of real-life behavior over time as a criterion for classification of individuals as “successful” or “unsuccessful” self-regulators, use of sophisticated and continuous measurement of physical activity over time (i.e., triaxial accelerometry), and use of a realistic and meaningful time frame for projection of behavioral intentions (1 week). As such, this investigation adds significantly to the rich database of high-quality laboratory experimentation on regulation of discrete behaviors (e.g., eye movements, button pressing) to include human behavior as it occurs in the natural environment.

There are several implications of these findings that bear mention. First, if it is true that the prefrontal areas form a self-regulatory circuit that facilitates translation of intention into behavior, this may suggest that individual differences in the ability to effortfully and consistently regulate behavior in healthy directions over the course of one’s lifetime may have implications for mortality, particularly that which stems from chronic illnesses whose causal factors include unhealthy—but immediately rewarding—behavioral tendencies aggregating over long periods of time (e.g., cardiovascular diseases, diabetes, and lung cancer). As such, these findings add to the growing literature suggesting that health behavior may be a mediating variable for observed associations between IQ and mortality. A second major implication of this research is theoretical. To the extent that this and other studies (Hall et al., 2008; Hart et al., 2005) point to a close association between cognitive ability and health behavior tendencies, it might suggest that biologically imbued self-regulatory abilities need to be modeled explicitly in theoretical accounts of individual health behavior. At present, none of the dominant models of health behavior include self-regulatory capacity explicitly.

Finally, an understanding of the self-regulatory demands of a given behavior may lead us to fundamentally rethink the enterprise of health promotion, which is frequently based on the assumption that motivation is the final (and only) pathway to health behavior and eventual health outcomes. Ironically, an understanding of cognitive function and self-regulation may suggest a stronger role for ecological intervention so as to reduce the self-regulatory demands of healthy behaviors (e.g., removing environmental barriers to physical activity) and to increase the self-regulatory demands of unhealthy behaviors (e.g., legislating public smoking bans). Indeed, the accumulating evidence suggests that such ecological determinants of health behavior performance might be more important than once thought (e.g., Fichtenberg & Glantz, 2002; Frank, Andresen, & Schmid, 2004; Saelens, Sallis, & Frank, 2003; Sallis, Bauman, & Pratt, 1998). The phrase, “making healthy choices easy choices” is a popular mantra of the public health movement, and new findings from social neuroscience—in concert with existing behavioral research—may have much to contribute to our understanding of the person–environment transactions that facilitate or impede the realization of this important objective.
References


Psychological Corp. *Wechsler Abbreviated Scale of Intelligence manual.*


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