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Is the smartphone a smart choice? The effect of smartphone separation on executive functions

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A B S T R A C T

Despite a huge spike in smartphone overuse, the cognitive and emotional consequences of smartphone overuse have rarely been examined empirically. In two studies, we investigated whether separation from a smartphone influences state anxiety and impairs higher-order cognitive processes, such as executive functions. We found that smartphone separation causes heightened anxiety, which in turn mediates the adverse effect of smartphone separation on all core aspects of executive functions, including shifting (Experiment 1) and inhibitory control and working-memory capacity (Experiment 2). Interestingly, impaired mental shifting was evident regardless of the extent of smartphone addiction, whereas smartphone addiction significantly moderated the negative effect of smartphone separation on inhibitory control, as assessed by the Stroop task. The study sheds light on cognitive mechanisms that may underlie some of these negative consequences of smartphone overuse.

1. Introduction

With the rapid rise of smartphone usage in recent years, smartphone devices have become a ubiquitous part of our culture and revolutionized how we live. Although smartphones have become an integral part of our lives and made our lives much smarter and more efficient, they can also have negative effects, including growing dependency, if not addiction. Not surprisingly, recent studies have shown that college students check their phones 60 times a day on average, with daily usage of more than 4 h (Harman & Sato, 2011; Kang & Jung, 2014; Lepp, Barkley, & Karpinski, 2014). In a 2015 study by the Pew Research Center, nearly half of Americans (46%) reported that they “couldn't live without” their smartphones, and 93% of young people (aged 18–29) used their smartphones throughout the day just to avoid boredom. Another survey (SecurEnvoy, 2012) found that 66% of smartphone users employed in the U.K. reported having “nomophobia,” which is the fear of being out of contact with one's smartphone.

This steady rise in smartphone use has triggered interest in the psychological consequences of smartphone dependency. Specifically, Billieux, Van der Linden, and Rochat (2008) have shown that problematic mobile phone use is associated with impulsive behaviors and lack of perseverance. Similarly, Hadlington (2015) found that adults with problematic mobile phone use were more prone to demonstrate cognitive failures in daily life, and Thornton, Faires, Robbins, and Rollins (2014) found that the mere presence of the experimenter's smartphone impaired college students' cognitive performance, which suggests that simply being reminded of one's smartphone can evoke anxiety and adversely affect cognitive functioning. Other studies have identified more wide-ranging negative outcomes associated with problematic smartphone use, including poor academic performance (e.g., Rosen, Carrier, & Cheever, 2013), poor sleep quality (Li, Lepp, & Barkley, 2015), and decreased mental health (Harwood, Dooley, Scott, & Joiner, 2014).

In light of these psychological consequences of smartphone dependency, an intriguing question arises: How much greater, potentially, would the negative influence be when people are separated from their smartphones and unable to access them? If people frequently have the urge to check social media and post updates, smartphone separation—i.e., being without the smartphone—would likely induce discomfort, anxiety, and potential cognitive impairment, which in turn might negatively affect many aspects of our daily life. In support of this notion, recent studies have found that the inability to connect with technology as frequently as desired is associated with a higher level of anxiety

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(Rosen, Carrier, et al., 2013; Rosen, Whaling, Rab, Carrier, & Cheever, 2013).

Several theories have been proposed to explain why smartphone separation would induce anxiety. According to the extended self theory (Belk, 2013), since the smartphone is perceived as an extension of the self, smartphone separation induces perceived loss of self, which in turn causes anxiety. Consistent with this view, Clayton, Leshner, and Almond (2015) found that self-reported extended self decreased when participants were unable to answer their ringing mobile phones. Another theory postulates that smartphone-separation anxiety results from the fear of missing out (FoMO) on an interesting event, experience, or conversation that might be occurring in one's social circle (Przybylski, Murayama, DeHaan, & Gladwell, 2013).

In line with these theoretical predictions, if smartphone separation results in greater anxiety, college students may be the most vulnerable to the negative consequences of separation from their smartphones because they are more closely attached to them than any other age group. Specifically, according to the 2015 Student Mobile Device Survey (Pearson, 2015), 85% of college students in the U.S. own a smartphone, 86% regularly use one, and nearly all have wireless Internet access at both home and school. In the same vein, younger college students (ages 18 to 19) have shown the highest smartphone usage (91%) relative to either older students (85%; ages 20 to 24) or young adults (81%; ages 25 to 30). Moreover, college students adopt smartphones relatively earlier than others and rely on them to a greater extent (Anderson, 2015; Lee, 2014; Smith, 2015; Yildirim & Correia, 2015). Not surprisingly, recent studies have found that college students become anxious when asked to put their smartphones out of sight (Cheever, Rosen, Carrier, & Chavez, 2014). Similarly, Clayton et al. (2015) observed significant increases in heart rate and blood pressure when college students were unable to respond to their ringing smartphones, which in turn disrupted their performance on a word-search puzzle. Consistent with this, Stothart, Mitchum and Yehnert (2015) found that receiving a cell-phone notification, even when one did not view or respond to it, triggered worrisome thoughts and impaired sustained attention, i.e., the ability to remain vigilant over time. Taken together, college students are more likely to experience heightened levels of anxiety when they are separated from their smartphones due to habitual and addictive smartphone behaviors (Van Deursen, Bolle, Hegner, & Kommers, 2015).

In light of these negative emotional consequences among college students, especially when smartphone use is banned or discouraged, we sought to determine whether smartphone separation adversely affects college students' higher-level cognitive skills (i.e., executive functions), which play a pivotal role in regulating thoughts and actions (Miyake et al., 2000). Executive functions (EFs) consist of related but separable cognitive processes: (a) inhibitory control to suppress prepotent responses, (b) shifting between tasks or mental sets, and (c) updating working-memory representations (for a review, see Miyake et al., 2000). We focused on EFs, as they have been shown to be closely linked to many crucial aspects of life, such as academic achievement, job success, interpersonal relationships, and mental health (Diamond, 2013). Given the literature that has consistently shown that anxiety impairs EFs (e.g., Ansari & Derakshan, 2010; Darke, 1988; Derakshan, Smyth, & Eysenck, 2009), it is plausible that if smartphone separation causes anxiety, it will adversely affect EFs. Despite the issue's critical importance, however, little is known about the cognitive consequences of smartphone separation.

We set out to investigate the impact of smartphone separation on the core aspects of EF: shifting between tasks or mental sets (i.e., cognitive flexibility) using the task-switching paradigm (Experiment 1) and inhibitory control and working-memory capacity using the Stroop and complex rotation-span tasks, respectively (Experiment 2). We also examined the mediating effect of anxiety and the moderating effect of smartphone addiction on the relationship between smartphone separation and EFs. Given that college students are likely to be heavy smartphone users, we focused on them because they should also be the most vulnerable to negative consequences when separated from their smartphones (Anderson, 2015; Lee, 2014; Smith, 2015; Yildirim & Correia, 2015). Drawing on previous research, we hypothesized that if smartphone separation creates greater anxiety, it will significantly mediate the effect of smartphone separation and, in turn, substantially impair performance on tasks that measure EF. Moreover, given that smartphone separation is likely to be markedly uncomfortable, especially with increasing addiction to smartphone use, we hypothesized that smartphone addiction will significantly moderate the effect of smartphone separation on EFs.

2. Experiment 1

Using the color-shape switching task, we investigated whether smartphone separation would affect cognitive flexibility (i.e., shifting aspects of EF) as indicated by switch costs, which are based on an ability to flexibly alternate between two different tasks. Our primary hypothesis is that if smartphone separation impairs cognitive flexibility, it will increase switch costs. We included control variables to control for any group differences in nonverbal intelligence, as assessed by the Kaufman Brief Intelligence Test, Second Edition, and positive and negative affect, as assessed by the International Positive and Negative Affect Schedule Short Form.

2.1. Participants

Eighty-seven undergraduate students (mean age = 21.6, range = 18–29 years, $SD = 2.11$) from a local university in Singapore participated for either extra course credit or S$5. One participant's data were excluded from the analysis because he/she did not comply with the instruction and refused to give his/her smartphone to the experimenter, which was our key experimental manipulation.

Overall, our participants had above average IQ scores, with a mean of 106.7 ($SD = 14.8$) when assessed by the KBIT-2 Nonverbal Matrices subtest (Kaufman & Kaufman, 1990). Participants came from varying SES levels, as indexed by participants' monthly household income in Singapore dollars: less than S$2500 (16.3%): S$2500–S$4999 (24.4%); S$5000–S$7499 (18.6%); S$7500–S$9999 (8.1%); S$10,000–S$12,499 (7.0%); S$12,500–S$14,999 (7.0%); S$15,000–S$17,499 (7.0%); S$17,500-S$19,999 (3.5%); and more than S$20,000 (8.1%).

2.2. Materials

2.2.1. Color-shape switching task

We employed a well-established task-switching paradigm to examine switch costs, which reflect the shifting aspects of EF (Hartanto & Yang, 2016; Monsell, 2003; Rubin & Meiran, 2005). Participants were asked to respond as fast and accurately as possible to either the color (red or green) or shape (circle or triangle) of the bivalent target stimulus according to the given cue (i.e., the color gradient as the color cue or a row of small black shapes as the shape cue). There were two bivalent target stimuli, i.e., a red triangle or a green circle. Participants were required to press the left key for either "green" or "triangle" and the right key for either "red" or "circle" (counterbalanced across participants). Throughout the task, the target stimulus did not match a response on both color and shape.

For each trial, a fixation cross appeared for 350 ms and was followed by a blank screen for 150 ms. Subsequently, the cue appeared for 250 ms and was followed by the target. Each participant completed one practice block (30 trials each); two pure blocks (color and shape blocks of 50 trials each, with the order counterbalanced); and four mixed blocks (25 switch and 25 non-switch trials each, semi randomized with a maximum of 4 consecutive trials of the same task).

2.2.2. Shortened version of the state-trait anxiety inventory (STAI)

The shortened version of the STAI (Marteau & Bekker, 1992) was used to measure participants' state anxiety ($\alpha = 0.79$). To ensure that participants did not suspect the link between smartphone separation and the anxiety scale, we embedded the STAI and, to assess mood, the International Positive and Negative Affect Schedule-Short Form (I-PANAS-SF; Thompson, 2007) into a single-sheet questionnaire, using a 5-point Likert scale.

2.2.3. Smartphone addiction scale short version (SAS)

The Smartphone Addiction Scale (Kwon, Kim, Cho, & Yang, 2013) was used to assess participants' degree of smartphone addiction. The scale consists of 10 items rated on a 5-point Likert scale. Scores for the 10 items were summed to create the addiction score (Cronbach's alpha = 0.83). According to Kwon et al. (2013), the cut-off value to be considered as smartphone addiction is 31 for males and 33 for females.

2.2.4. Kaufman brief intelligence test second edition (K-BIT 2) matrices subtest

The K-BIT-2 matrices subtest (Kaufman & Kaufman, 1990) was used to assess participants' nonverbal fluid intelligence. Participants were presented with a series of images and asked to complete visual analogies of the target stimulus. The standardized score has a mean of 100 and a standard deviation of 15.

2.2.5. International positive and negative affect schedule short form (I-PANAS-SF)

The I-PANAS-SF (Thompson, 2007) was used to measure participants' state emotion. The scale contains five items to measure positive affect (PA; $\alpha = 0.79$) and five items to measure negative affect (NA; $\alpha = 0.72$) on a 5-point Likert scale.

2.3. Procedure

Each session was randomly assigned to be either the separation or non-separation (i.e., control) condition. In the separation condition, participants and a confederate entered the laboratory and were seated individually in adjacent open cubicles. Participants were first asked to complete the KBIT-2. Upon completion, the confederate's smartphone rang for about 5 s before she rejected the call and put her smartphone on vibration mode. After another 5 s, the confederate's phone rang again, vibrating loudly for 7 s. The experimenter approached the confederate and offered to keep her smartphone for her during the rest of the experiment. The experimenter then made the same offer to the participants; one objected, and his/her data was removed from analysis. In the non-separation condition, however, the experimenter approached both the confederate and the participants and asked them to put their smartphones into silent and non-vibrating mode.

Next, participants read instructions on the computer for the subsequent color-shape switching task. After this a short survey on state anxiety (STAI) and mood (I-PANAS-SF) was administered to ensure that participants did not suspect the smartphone-separation manipulation, After completing the survey, participants performed the color-shape switching task, which was followed by the SAS and a questionnaire that asked about their frequency of smartphone usage and demographics (age, sex, and household income).

2.4. Results

As expected, participants in the separation condition reported significantly greater anxiety than those in the non-separation condition, suggesting that smartphone separation induced heightened anxiety (see Table 1). The two groups did not differ, however, in other aspects of emotionality, nonverbal intelligence, or household income as a proxy of SES, all of which are known to affect EF (Sarsour et al., 2011; Unsworth, Fukuda, Awh, & Vogel, 2014; Yang & Yang, 2014; Yang, Yang, & Isen, 2013). They also did not differ in degree of smartphone usage or smartphone addiction.

2.4.1. Switch costs

Given that switch cost arises when two different tasks alternate, we computed it by subtracting the mean response times (RT) on non-switch (repeat) trials from those of switch trials in mixed blocks. RTs that were either 2.5 *SD* above or below an individual's mean were excluded separately for pure blocks and mixed-task blocks. A repeated-measures mixed-factor ANOVA was performed with Smartphone Separation (separation vs. non-separation) as a between-participant factor and Task-switching (task-switch trials vs. non-switch trials) as a within-participant factor. We found the main effects of Smartphone Separation, $F(1, 84) = 8.69$, $p = 0.004$, $\eta_p^2 = 0.094$, and Task-switching (i.e., switch costs), $F(1, 84) = 327.44$, $p < 0.001$, $\eta_p^2 = 0.796$. Consistent with our prediction, we found a significant interaction between Smartphone Separation and Task-switching, $F(1, 84) = 18.27$, $p < 0.001$, $\eta_p^2 = 0.179$, which suggests that smartphone separation modulates task-switching efficiency. Simple effect analyses showed that smartphone separation increased switch costs by impairing participants' performance more on task-switch trials than on non-switch (i.e., task-repeat) trials (Table 2).

We conducted similar repeated-measures mixed-factor ANOVA on the accuracy data and found the main effect of Task-switching, $F (1, 84) = 161.81$, $p < 0.001$, $\eta_p^2 = 0.658$. However, accuracy data yielded neither the main effect of Smartphone Separation, $F (1, 84) = 0.07$, $p = 0.791$ $\eta_p^2 = 0.001$, nor the interaction between Smartphone Separation and Task-switching, $F (1, 84) = 0.00$, $p = 0.982$, $\eta_p^2 = 0.000$.

Importantly, we performed a mediation analysis on RT data to determine whether state anxiety induced by smartphone separation mediated the effect of smartphone separation on switch costs. Multiple mediation models were estimated through the PROCESS macro (Hayes, 2009). The bias-corrected bootstrap resampling method (10,000 samples) showed that state anxiety significantly mediated the relationship between smartphone separation and switch costs, 95% CI [4.16, 46.48]. The residual direct effect indicated partial mediation of anxiety between smartphone separation and switch costs, $p = 0.0004$ (Fig. 1).

We also performed a moderation analysis to determine whether smartphone addiction moderates the relationship between smartphone separation and switch costs. Regression analyses showed that smartphone separation significantly predicted switch costs, $B = 133.26$, $p <$ 001, but smartphone addiction did not, $B = -1.20$, $p = 0.600$. Importantly, smartphone addiction did not moderate the relationship between smartphone separation and switch costs, $B = -2.05$, $p = 0.647$, indicating the robust effect of smartphone separation on switch costs, irrespective of the extent of smartphone addiction.

Table 1
Participant demographics, intelligence, smartphone-related behaviors, and affective states.

	Experiment 1			Experiment 2		
	Separated	Non-separated	t	Separated	Non-separated	t
Age	21.5 (2.34)	21.7 (1.83)	−0.42	21.6 (2.09)	21.3 (1.60)	0.61
Household income (SES)[a]	3.86 (2.37)	3.77 (2.65)	−0.24	3.80 (2.54)	4.52 (2.45)	−1.16
KBIT-2 (standardized score)	109.18 (15.72)	104.02 (13.46)	1.62	102.43 (17.54)	107.13 (18.71)	−1.05
Smartphone usage (hours per day)	6.80 (3.98)	8.31 (5.18)	−1.52	6.29 (3.55)	7.09 (5.66)	−1.41
Smartphone checking (times per day)	76.2 (44.43)	79.9 (50.89)	−0.34	80.29 (56.96)	61.32 (41.91)	1.52
Smartphone addiction[b]	32.38 (8.10)	33.37 (8.61)	−0.55	31.26 (7.68)	30.29 (9.33)	−0.46
State anxiety	2.55 (0.78)	2.15 (0.75)	2.45*	2.71 (0.99)	2.08 (0.84)	2.76*
Positive affect	2.62 (0.71)	2.71 (0.82)	−0.51	2.85 (0.68)	3.05 (0.74)	−1.13
Negative affect	1.59 (0.63)	1.39 (0.52)	1.60	1.75 (0.77)	1.49 (0.66)	1.47

Note.
*$p < 0.05$.
**$p < 0.001$.
[a] Household income was rated on a scale of 1 (less than S$2500) to 9 (more than S$20,000), with intervals of S$2500 in Singapore dollars.
[b] The cut-off values of 31 for males and 33 for females are indicative of an addictive level of smartphone usage. *SD*s are shown in parentheses.

Table 2
Reaction times (RT), accuracy, and switch costs as a function of smartphone separation (Experiment 1).

	Reaction time (RT)			Accuracy		
	Separated	Non-separated	t	Separated	Non-separated	t
Type of trials						
Pure	413 (75.9)	419 (76.6)	−0.35	0.97 (0.07)	0.98 (0.03)	−0.88
Repeat	808 (228.5)	724 (192)	1.83†	0.96 (0.05)	0.95 (0.06)	0.32
Switch	1160 (302.3)	942 (253.3)	3.61*	0.88 (0.08)	0.88 (0.10)	0.21
Switch Costs	351 (160.5)	217 (127.3)	4.27**	−0.08 (0.06)	−0.08 (0.06)	0.02

Note. *SD*s are shown in parentheses.
†$p < 0.10$; *$p < 0.05$; **$p < 0.001$.

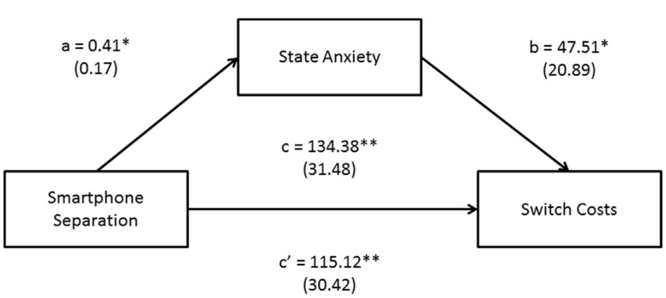

Fig. 1. Results from Experiment 1: mediation model showing the influence of smartphone separation manipulation (0 = control group; 1 = separated group) on switch costs, as mediated by anxiety. a, b, c and c′ represent path coefficients in unstandardized forms, and standard errors are shown in parentheses. c and c′ represent total effect and direct effect, respectively. *Note.* *$p < 0.05$, **$p < 0.001$.

2.5. Discussion

We found that smartphone separation impaired the shifting aspect of EF—i.e., cognitive flexibility—due to the anxiety it produces. Notably, the negative effect of smartphone separation was present regardless of the degree of smartphone addiction. Although these findings are intriguing, it is still unclear whether heightened anxiety in the smartphone-separation condition is due to smartphone separation or simply having to relinquish a valuable possession to a stranger. Therefore, Experiment 2 was designed to clarify the source of the induced anxiety by requiring participants in the control condition to relinquish a similarly valuable possession—their national identification card—to a stranger. With this change, we aimed to examine the relationship between smartphone separation and other key aspects of EF, i.e., inhibitory control and working memory.

3. Experiment 2

In Experiment 2, we examined inhibitory control and working memory as assessed by the classic Stroop task (Stroop, 1935) and rotation-span task (Foster et al., 2014), respectively. As found in Experiment 1, we conjectured that yielding one's smartphone to an experimenter—which is comparable to relinquishing a valuable possession—would lead to a high level of anxiety. Consequently, we predicted that participants in the separation condition would perform worse on the Stroop task and rotation-span tasks than those in the control condition. We also predicted that anxiety would mediate the effect of smartphone separation on inhibitory control and working-memory capacity. Moreover, although smartphone addiction did not moderate the effect of smartphone separation on switch costs in Experiment 1, we predicted that smartphone addiction would have different moderating effects on inhibitory control and working-memory capacity, because those two aspects of EF are closely related to the regulatory system, which is more likely to be impaired by problematic use of a smartphone.

3.1. Participants

Seventy undergraduate students with an average age of 21.4 ($SD = 1.87$; range = 19–29) were recruited from a local university in Singapore for either extra course credit or S$5. Four were excluded from the analysis: Two did not have their smartphones, and two were highly distracted and did not comply with the instruction. In total, 66 (female = 38) participants were randomly assigned to either the smartphone-separation ($n = 35$) or the control condition ($n = 31$).

Overall, our participants were frequent smartphone users; they reported spending approximately 7.1 h a day ($SD = 4.7$) on their smartphones and checked them 71 times per day ($SD = 50.98$).

Additionally, they had above-average IQs, with a mean of 104.6 ($SD = 18.1$), and were from varying SES levels in terms of monthly household income (in Singapore dollars): less than S$2500 (7.6%): S$2500–S$4999 (28.8%); S$5000–S$7499 (18.2%); S$7500-S$9999 (6.1%); S$10,000–S$12,499 (13.6%); S$12,500–S$14,999 (4.5%); S$15,000–S$17,499 (6.1%); S$17,500-S$19,999 (6.1%); and more than S$20,000 (9.1%).

3.2. Materials

The same materials were used as in Experiment 1: the nonverbal measure of intelligence (KBIT-2), the Smartphone Addiction Scale Short Version (SAS; $\alpha = 0.84$), the International Positive and Negative Affect Schedule Short Form (I-PANAS-SF; PA, $\alpha = 73$; NA, $\alpha = 0.76$), and the shortened version of the State-Trait Anxiety Inventory (STAI; $\alpha = 0.84$). Two additional tasks were used to assess EF, as follows.

3.2.1. The rotation-span task

The rotation-span task, which was adapted from Foster et al. (2014), assesses working-memory capacity using a complex span task that has been reliably shown to tap working memory (Foster et al., 2014; Shah & Miyake, 1996). Participants were presented with a sequence of either short or long arrows, each of which pointed in one of two directions. After each arrow, participants completed a distraction task in which they judged whether a rotated letter mirrored the target letter. They were then asked to recall the length and direction of arrows. Set size (i.e., the total number of arrows to remember in a trial) varied from 2 to 5 per trial.

3.2.2. The Stroop task

A nonverbal version of the classic Stroop task (Stroop, 1935) assessed inhibitory-control processing. In the task, color words (red, green, yellow, and blue) appeared on the computer screen in either the same (congruent) or a different (incongruent) ink color—e.g., the word “red” in blue ink. Participants were instructed to press a key marked “R”, “G”, “B”, or “Y” on the keyboard for its corresponding ink color. Each trial began with a fixation point (500 ms), followed by the target stimulus. When the key was pressed, feedback was shown for 500 ms followed by a blank screen (i.e., intertrial interval) of 500 ms. The task consisted of 16 practice trials and 36 congruent and 36 incongruent trials.

3.3. Procedure

Each session was randomly assigned to be either the separation or non-separation (control) condition. On arrival, participants were taken to a closed room to register their attendance. Participants in the smartphone-separation condition were asked to relinquish their smartphones to avoid potential disruptions during the study. Those in the control condition were asked to relinquish their national identification cards for registration, which they were told would be completed by the experimenter during the experiment; if the participant did not have his or her national identification card, the student identification card was used instead. After participants left their belongings (either their smartphone or ID) in the reception room, they moved to another room (i.e., separation from the smartphone or ID was enacted by a physical distance of approximately 5 m from the reception room), where they completed a short questionnaire on anxiety and mood. The rotation-span and Stroop tasks were performed in that order, with a short break in between. After being given their belongings, participants completed the nonverbal intelligence measure (the K-BIT-2), the Smartphone Addiction Scale (SAS), and a background questionnaire.

3.4. Results

Participants in the separation condition reported significantly greater anxiety than those in the control condition, suggesting that smartphone separation—rather than separation from an equally valuable possession—induced anxiety (see Table 1). The two groups did not differ, however, in terms of intelligence, SES, smartphone use, or addiction level (see Table 1).

3.4.1. The Stroop task

Response latencies that were either 2.5 *SD* above or below each individual's mean were excluded. Inaccurate responses were also excluded from the analyses. A repeated-measures mixed-factor ANOVA was performed on RT data, with Smartphone Separation as a between-participant factor and Stroop trials (congruent vs. incongruent) as a within-participant factor. We found a significant Stroop effect, $F(1, 64) = 189.75$, $p < 0.001$, $\eta_p^2 = 0.748$, and an interaction between smartphone separation and Stroop effect, $F(1, 64) = 4.73$, $p = 0.033$, $\eta_p^2 = 0.069$. Similar patterns occurred in accuracy data: a Stroop effect, $F(1, 64) = 51.47$, $p < 0.001$, $\eta_p^2 = 0.446$, and an interaction between Smartphone separation and the Stroop effect, $F(1, 64) = 5.28$, $p = 0.025$, $\eta_p^2 = 0.076$ (see Table 3), which indicate that participants in the smartphone-separation condition exhibited a greater Stroop effect in terms of both RT and accuracy than those in the control condition.

We performed two separate mediation analyses on both RT and accuracy data to determine whether anxiety mediated the relationship between smartphone separation and Stroop effect. The bias-corrected bootstrap resampling method (10,000 samples) showed that anxiety significantly mediated the effect of smartphone separation on the RT-based Stroop effect, 95% CI [0.84, 37.10], but not the accuracy-based Stroop effect, 95% CI [−0.02, 0.00]. The residual direct effect revealed full mediation effects for RT, $p = 0.133$, but not accuracy, $p = 0.093$ (Fig. 2).

Separate moderation analyses were conducted on RT and accuracy data to determine whether smartphone addiction moderates the relationship between smartphone separation and the Stroop effect. Smartphone addiction significantly influenced the Stroop effect in RT, $B = 4.30$, $p = 0.001$, and the effect of smartphone separation remained significant, $B = 47.23$, $p = 0.028$, even after controlling for smartphone addiction. Notably, smartphone addiction moderated the negative effect of smartphone separation on the RT-based Stroop effect, $B = 7.80$, $p = 0.003$, but not on the accuracy-based Stroop effect, $B = 0.00$, $p = 0.308$ (Fig. 3).

3.4.2. The rotation-span task

We excluded 4 participants whose accuracy for judging the rotated letter was below 65%; given that some aspects of our study induce anxiety, we employed a more lenient criterion than the conventional cut-off point of 80%–85% (Conway et al., 2005). Working-memory capacity was computed using the partial-credit unit method, in which the participant's score was expressed as the proportion of the total number of correct recall responses in a set (Conway et al., 2005). An independent-samples *t*-test showed a significant effect of smartphone separation, $t(60) = 1.98$, $p = 0.052$, $d = 0.52$ (Table 4).

Mediation analysis showed that anxiety significantly mediated the relationship between smartphone separation and working-memory capacity, 95% CI[−0.89, −0.02] (Fig. 4). The direct effect indicated full mediation, $p = 0.192$. Moderation analysis, however, showed that smartphone addiction did not moderate the effect of smartphone separation on working-memory capacity, $B = -0.50$, $p = 0.475$.

Table 3
Reaction time (RT), Accuracy, and the Stroop Effect as a Function of Smartphone Separation (Experiment 2).

	Reaction time (RT)			Accuracy		
	Separated	Control	t	Separated	Control	t
Trial type						
Congruent	701 (156)	655 (141)	1.24	0.97 (0.53)	0.99 (0.23)	-2.14^{*}
Incongruent	888 (240)	791 (169)	$1.87^{\dagger}$	0.91 (0.08)	0.96 (0.04)	-3.01^{*}
Stroop effect	186 (114)	135 (65)	2.18^{*}	−0.06 (0.06)	−0.03 (0.04)	-2.30^{*}

Note. *SD*s are shown in parentheses.
$^{\dagger}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.001$.

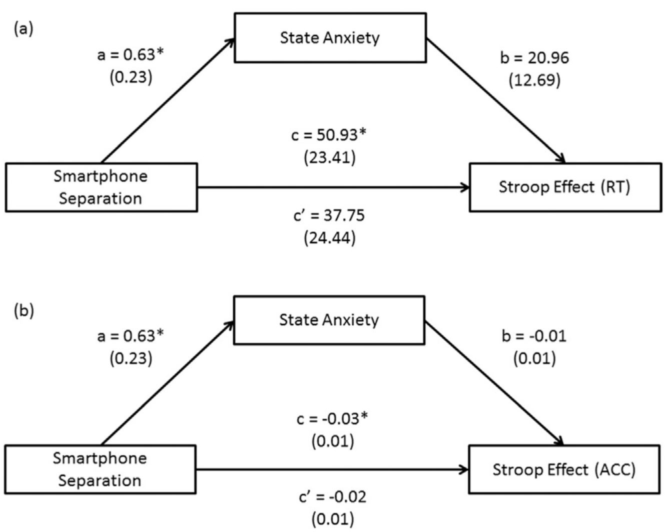

Fig. 2. Results from Experiment 2: Mediation models demonstrate the influence of smartphone separation on the Stroop effect in RT (panel A) and accuracy (panel B), as mediated by anxiety. *Note*. a, b, c and c'represent path coefficients in unstandardized forms, and standard errors are shown in parentheses. c and c'represent total effect and direct effect, respectively. $^{*}p < 0.05$, $^{**}p < 0.001$.

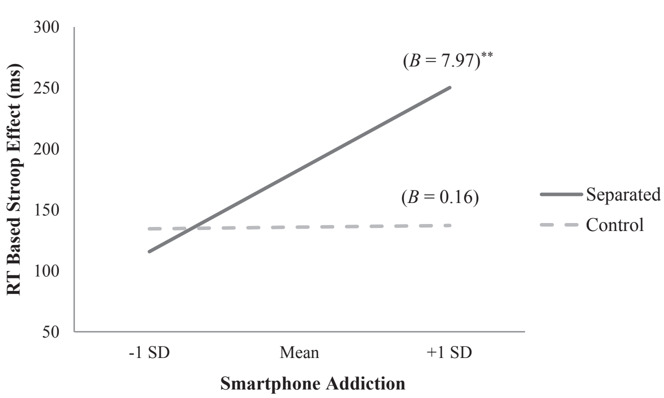

Fig. 3. Results from Experiment 2: The effect of smartphone separation on the Stroop effect was moderated by smartphone addiction. Simple slops (i.e., unstandardized coefficients) of smartphone addiction predicted the Stroop effect for 1 *SD* above the mean of smartphone addiction and 1 *SD* below the mean of smartphone addiction. $^{*}p < 0.05$, $^{**}p < 0.001$.

3.5. Discussion

Consistent with previous results, we found that smartphone separation impaired inhibitory control and working memory (i.e., updating), which were assessed by the Stroop and rotation-span tasks, respectively. Importantly, the effects of smartphone separation were fully mediated by anxiety caused by smartphone separation—rather than separation from another important possession—which suggests that anxiety is the primary mechanism underlying the negative effect of smartphone separation on higher-order executive functioning. Notably, smartphone addiction significantly influenced the Stroop effect and moderated the effect of smartphone separation on RT-based Stroop effect only, but not on working-memory capacity, which suggests that smartphone addiction leads to poorer interference control and intensifies the negative effect of smartphone separation on interference control.

4. General discussion

Consistent with theoretical predictions based on the extended self theory (Belk, 2013) and FoMO (Przybylski et al., 2013), our study demonstrates that smartphone separation results in heightened anxiety. Moreover, we found that smartphone-separation anxiety mediates the adverse effects of smartphone separation on all core aspects of EF: Participants who had been separated from their smartphones performed significantly worse on tasks that assessed task-switching, inhibitory control, and working memory capacity. Importantly, we found that smartphone addiction did not moderate the negative effect of smartphone separation on shifting aspects of EFs, which suggests that the adverse effect of smartphone separation on those EFs can be predominant among various users, regardless of the extent of their smartphone addiction. However, our regression analyses showed that when we controlled for smartphone separation, anxiety, and nonverbal fluid intelligence, smartphone addiction significantly predicted greater Stroop interference ($B = 3.31$, $p = 0.017$) and moderately predicted impaired working-memory capacity ($B = -0.15$, $p = 0.092$). These results suggest that smartphone addiction is associated with poorer inhibitory and regulatory control of cognitive performance. Taken together, our findings contribute to the literature by demonstrating that smartphone separation has not only emotional but also cognitive consequences for college students.

In light of these findings, it is important to note that the increase in smartphone use has also had positive effects: These devices have been shown to enhance the quality of our experiences in such settings as education (Shin, Shin, Choo, & Beom, 2011) and health care (Forman et al., 2014). However, our findings serve as a clear warning about the potential side effects of smartphone usage for impaired higher-order cognitive abilities, especially when restricted access triggers anxiety.

Our study sheds light on the psychological and behavioral consequences of problematic smartphone dependency—e.g., anxiety, attention deficits, impulsiveness, and addiction (Kim, 2013). Given that EFs are major control mechanisms that underlie various forms of self-regulation, an impaired self-regulatory system due to smartphone-separation anxiety may intensify a vicious cycle in which separation from one's smartphone creates an even stronger urge to use it to excess as a means of relieving emotional distress.

Table 4
Working-memory performance as assessed by the rotation-span task (Experiment 2).

	Separated ($n = 34$)	Control ($n = 28$)	t
Working-memory score (in partial-credit units)	5.16 (2.01)	6.04 (1.32)	$-1.98^{\dagger}$
RT on rotation decision	1042 (419)	931 (215)	1.27
Accuracy on rotation decision	0.87 (0.93)	0.91 (0.10)	-1.58

Note. *SD*s are shown in parentheses. $^{\dagger}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.001$.

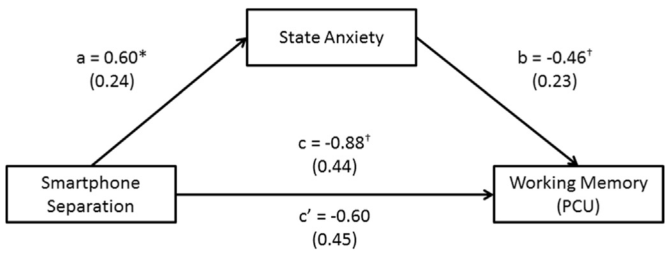

Fig. 4. Results from Experiment 2: The mediation model demonstrates the influence of smartphone separation on working-memory capacity, as mediated by anxiety. *Note.* Coefficients are unstandardized with standard errors in parentheses. c and c'represent total effect and direct effect, respectively. $\dagger p < 0.10$, $^{*}p < 0.05$, $^{**}p < 0.001$.

This heightened anxiety, combined with the impaired control abilities we have documented during smartphone separation, explains why a recent large-scale study found that media abstinence (i.e., no media usage), even for a day, is difficult for the great majority of college students (Moeller, Powers, & Roberts, 2012). Unless students are able to manage the attendant anxiety and strengthen their regulatory skills, efforts to refrain not only from media in general, but smartphones in particular, are likely to fail.

Our findings are in line with the theoretical Pathways Model of Problematic Mobile Phone Use (PMPU; Billieux, Maurage, Lopez-Fernandez, Kuss, & Griffiths, 2015). Billieux et al. (2015) proposed three potential pathways—excessive reassurance, impulsive, and extraversion—that have been found to result in addictive, antisocial, or risky patterns of problematic mobile phone use. Notably, within Billieux's excessive reassurance pathway, general anxiety, social anxiety, neuroticism, and emotional instability are postulated as substantial risk factors for addictive patterns of mobile phone use, which suggests that, consistent with our findings, anxiety and emotional distress may be the primary locus of problematic mobile phone use. Therefore, in light of our findings and the Pathways model, mere smartphone abstinence may not be an effective treatment for smartphone addiction, as smartphone separation may raise anxiety to a more destructive level and impair both cognitive control and the regulatory system. Further research is warranted to determine how smartphone usage weakens self-regulation and whether poor self-regulation is an antecedent of smartphone addiction.

It is important to note the pedagogical implications of our findings. Recent studies have demonstrated that college students who frequently text or use social media when attending lectures or studying show poorer academic performance than their counterparts (Bellur, Nowak, & Hull, 2015; Junco, 2012). In view of the potentially negative effects of smartphone overuse on academic attainment, some may seek to prohibit smartphones in school. However, as noted above, a blanket restriction on smartphones in school is likely to be more harmful than beneficial, because smartphone separation triggers anxiety that, in turn, adversely affects students' cognitive functioning. Moreover, a long period of smartphone separation may induce even greater desire to use it and engender emotional problems and poorer cognitive regulation (i.e., EF), all of which would lower the quality of classroom learning.

Instead of banning smartphones entirely, allowing periodic technology breaks—during which students are allowed to use their smartphones—may lower their anxiety and thus be more effective in helping students regulate smartphone use and overcome their FoMO (Rosen et al., 2013). In a similar vein, Rosen, Cheever, and Carrier (2012) found that having a 1-min break for smartphone use after each 15-min study is effective in improving students' attentional focus in classroom settings.

Our study is not without caveats. First, although we found that smartphone separation induces anxiety, we cannot precisely determine the locus of participants' anxiety. For instance, it could be caused by either attachment to their smartphones (i.e., dependency) or fear of missing an exciting or interesting event that might be happening elsewhere (i.e., FoMO). Future research into the root locus of the mediating effect of anxiety between smartphone separation and impaired EF (Clayton et al., 2015; Przybylski et al., 2013), therefore, would be valuable. Second, although we focused on an emotional factor (i.e., anxiety) as a primary mediator, it is possible that other factors, such as motivation or personal characteristics, mediate the effect of smartphone separation in various ways. Third, one could question our decision to assess general state anxiety instead of anxiety specifically driven by smartphone separation. Although we acknowledge the assumed value of directly asking participants to indicate their level of anxiety caused by being separated from their smartphones, doing this shortly after the manipulation of smartphone separation could cause participants to feel self-conscious or suspicious of the experimenter's intent—which, in turn, could result in demand characteristics.

Since our study focused on college students, our findings may not be generalizable to younger children. Given the important implications of our findings, however, future studies should extend to younger children, who are growing up heavily exposed to smartphone devices. Moreover, since young children's cognitive control system is thought to be less mature than adults', it is critical that we determine whether these populations are more vulnerable to the adverse effects of smartphone overuse than adults. Finally, our results shed light on only one of the potential emotional and cognitive mechanisms that underlie problematic smartphone dependency and its associated regulatory behaviors. Future research will be required to develop strategies for treatment, intervention, and prevention.

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