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Examining cognitive function across the lifespan using a mobile application

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ABSTRACT

Many studies conducted in a laboratory or university setting are limited by funding, personnel, space, and time constraints. In the present study, we introduce a method of data collection using a mobile application that circumvents these typical experiment administration issues. Using the application, we examined cross-sectional age differences in cognitive function. We obtained data from more than 15,000 participants and replicated specific patterns of age-related differences in cognition. Using a subset of these participants, we also examined the processing speed account of age-related cognitive differences, and the association of exercise and leisure activity with cognitive function across the lifespan. We discuss the relative advantages and disadvantages of data collection with a mobile application, and provide recommendations for the use of this method in research.

1. Introduction

With the widespread use of the Internet and the rapid development of hand-held mobile devices and the applications that run on these devices, we have witnessed a rapid increase in research programs that take advantage of this technology. We have seen more exploratory research aimed at characterizing patterns and generalizing hypotheses using large datasets obtained by administering surveys or tests online. Conducting research online has the advantage of rapid, economical, and large data collection across a diverse population (Bohannon, 2011). In the social sciences, the vast amount of data from social networking websites such as Twitter and Facebook present an unprecedented opportunity to study human interaction, personality, and other lifestyle factors in diverse cultures in real time (Bollen, Pepe, & Mao, 2011; Dodds & Danforth, 2010; Mislove, Lehmann, Ahn, Onnela, & Rosenquist, 2010; O'Connor, Balasubramanyan, Routledge, & Smith, 2010; Trepte, Reinecke, & Juechems, 2012; Wu, Huang, Yen, & Popova, 2012). For example, Golder and Macy (2011) investigated how people's mood fluctuate throughout the day by scanning tweets of more than 2 million people from 84 countries. The results showed that mood peaks in the morning and declines in the afternoon, with this ''mood swing'' pattern appearing similar across various cultures and regions around the world. While the results are not novel, the important point of Golder and Macy's Twitter-based study was the ability to test and more widely generalize theories about human behavior using a huge amount of data from a heterogeneous population.

These technological changes provide the potential to develop alternative methods for studying human cognition. Traditional methods of investigating human cognitive processes such as memory, attention and language most often rely on small homogenous samples in controlled laboratory settings. For example, the commonly used method for research in cognitive aging is age-comparative design, which contrasts a group of young adults (typically college students) with community-dwelling older adults. The often limited age range and the lack of cultural and regional diversity in the convenience samples often lead to the problem of generalizing findings from the laboratory to the real world. Although recent attempts of using Internet-based technology for data collection (Killingsworth & Gilbert, 2010; Nosek et al., 2009) have allowed access to a wider population, cognitive assessment paradigms that are implemented over the Internet often do not provide the temporal precision of stimuli presentation and behavioral response measurement required for studies of human cognition. In contrast to traditional laboratory and Internet-based studies, data collection using mobile applications allows researchers to collect a large amount of data with cultural and regional diversity, and offers high temporal resolution with built-in millisecond timing for displaying stimuli and measuring behavioral responses (Dufau et al., 2011).

In the current study, we present results from data collected using the mobile application *BrainBaseline*. BrainBaseline is an

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application developed by Digital Artefacts, LLC, in conjunction with cognitive psychologists. BrainBaseline is composed of two main parts. One part is a survey of physical and leisure activity along with basic demographics, and another is a cognitive battery composed of 13 tasks. During a 4-month period, more than 15,000 users across a diverse age range and cultural background filled out survey information and took a self-selected subset of tasks.

The first goal of the current study was to demonstrate the validity of the mobile application in the study of human cognition. In order to achieve the first goal, we investigated the cross-sectional age effect in the 13 tasks in BrainBaseline. We also examined the processing speed account of age-related cognitive change or differences. Epidemiological research and laboratory studies have consistently shown that cognitive function changes as we age (McKay & Abrams, 1996; Salthouse, 1999; Smith, 1996). Increasing age is often associated with poorer cognition, especially on measures of visuo-spatial memory, processing speed and complex timed tasks. Also, previous studies have demonstrated a substantial reduction in age-related cognitive differences after measures of processing speed are factored out of the relationship between cognitive performance and chronological age (Cerella, 1991; Salthouse, 1996, 1999). We examined how well processing speed would account for the cross-sectional age effect by (1) conducting mediation analysis and (2) including a construct measure of processing speed as a covariate in the analyses of age-related differences in memory and attention.

The second goal of the current study was to demonstrate the potential of the mobile application to uncover mechanisms of human cognition and interactions with lifestyle factors that may not easily be observed in the noise of small-scale and homogenous samples. In order to achieve the second goal, we investigated the effect of exercise and video game experience on cognitive function and how these factors may interact with age. It is well known that physical exercise has a positive influence in maintaining or even improving cognitive and brain health throughout the lifespan (see Voss, Nagamatsu, Liu-Ambrose, and Kramer (2011) for review). Research supports a general benefit of aerobic fitness not only on childhood cognitive performance (Buck, Hillman, & Castelli, 2008; Castelli, Hillman, Buck, & Erwin, 2007; Chaddock et al., 2012; Sibley & Etnier, 2003), but also in elderly adults' cognitive performance (Colcombe & Kramer, 2003; Dustman et al., 1984; Kramer et al., 1999), and brain function (Burdett et al., 2010; Colcombe et al., 2004; Voss et al., 2010). Video game experience or training (Ball, Berch, Helmers, et al., 2002; Basak, Boot, Voss, & Kramer, 2008; Boot, Kramer, Simons, Fabiani, & Gratton, 2008) has been shown to enhance or slow the decline of cognitive abilities in both younger and older adults. Yet, most of these studies were performed on targeted age groups and did not examine the interaction between physical activity and age. Similarly, although several researchers have noted enhancements in various aspects of visual attention as a result of videogame play (Andrews & Murphy, 2006; Basak et al., 2008; Castel, Pratt, & Drummond, 2005; Chisholm, Hickey, Theeuwes, & Kingston, 2010; Clark, Fleck, & Mitroff, 2011; Colzato, van Leeuwen, van den Wildenberg, & Hommel, 2010; Green & Bavelier, 2003; Green & Bavelier, 2006a; Green & Bavelier, 2006b; Green & Bavelier, 2007; Trick, Jaspers-Fayer, & Sethi, 2005), these studies were limited to certain age groups (typically, college students). We examined how physical (exercise) and leisure (video game experience) activities interact and how they are associated with cognitive operations across the lifespan.

2. Methods

2.1. Participants

From December 2010 to April 2011, a total of 15,346 iPad users downloaded and used BrainBaseline. The number of participants who completed each task ranged from 2623 to 8360. Participation was voluntary and no monetary compensation was provided.

2.2. Profile information

In order to complete the cognitive tasks in BrainBaseline, users first created an account and entered their profile information. This profile information was voluntary and assessed participants' demographic information (i.e., gender, birth year, ethnicity, highest education, and income) and physical activity and leisure time activity. Current levels of self-reported physical activity were measured using the Godin Leisure Time Exercise Questionnaire (GLTEQ; Godin & Shephard, 1997), a well-validated measure of physical activity. Participants indicated the frequency of their participation in strenuous (e.g., jogging), moderate (e.g., fast walking), and mild (e.g., easy walking) exercise for periods of more than 15 min over the past 7 days. The weekly frequencies of strenuous, moderate, and mild activities were multiplied by 9, 5, and 3 metabolic equivalents, respectively, and summed to form a measure of total exercise time activity.

The leisure activity section assessed the number of languages a user could read or write in, hours per week spent playing video games, reading books, newspapers or magazines, surfing the web, watching television, sleeping, and learning a new language or new musical instrument (in the last 2 years). A summary of the participants' responses on the demographics, leisure and physical activity questionnaires is presented in Table 1.

2.3. Cognitive task battery

At the time of data collection, BrainBaseline's cognitive task battery was composed of 13 tasks: Visual Short-Term Memory (VSTM), Spatial Working Memory (SPWM), N-back, Simple Reaction Time (SRT), Go–No Go Reaction Time (Go–No Go), Digit-Symbol Substitution, Posner Cuing, Flanker, Stroop, Attentional Blink (AB), Visual Search, Task Switch, and Trail Making. These tasks were categorized into three cognitive constructs of memory, attention and processing speed. All cognitive tasks were composed of a short practice block and a main test block. Feedback was given only for the practice block and only trials from the test block were included in the analyses. A brief description of each task is presented in Table 2 and a detailed description of each task is presented in an Appendix A.

3. Results

3.1. Leisure and physical activity across age group

In all analyses, we excluded participants aged 1–9 due to the unreliability of the data. There was high within-group variability and a relatively small number of participants in this group compared to other groups. We divided participants into 6 age groups (10–19, 20–29, 30–39, 40–49, 50–59, and over 60) and conducted Analyses of Variance (ANOVA) on the various measures of leisure activity (new language learning experience in the last 2 years, new instrument learning experience in the last 2 years, hours of game play, hours of reading, hours of sleep, hours of watching TV, and hours of web-surfing) and physical activity. Age group was specified as a between-subjects factor. The main effect of age group was significant in all leisure and physical activity profiles: language learning experience $F(5,10926) = 467.16$, $p < .01$, new instrument learning experience $F(5,9603) = 276.2$, $p < .01$, hours of game play $F(5,10273) = 35.54$, $p < .01$, hours of reading $F(5,11681) = 26.96$, $p < .01$, hours of sleep $F(5,12040) = 169.90$, $p < .01$, hours of watching TV $F(5,11937) =$

Table 1
Demographics of participants by age group (standard deviations are in parentheses).

	1–9	10–19	20–29	30–39	40–49	50–59	60+	# Response /# total
Number of participants	200	2487	4019	3412	2785	1606	837	15,346/15,346
Mean age	7.0 (2.24)	15.31 (2.56)	24.74 (2.78)	34.14 (2.88)	44.22 (2.91)	54.05 (2.80)	66.17 (6.63)	15,346/15,346
Education	N/A	1.12 (.368)	2.51 (.865)	2.88 (.941)	2.89 (.945)	2.83 (1.005)	2.86 (1.064)	14,333/15,436
Proportion male (%)	43	30	40	43	38	34	39	15,295/15,346
Exercise score	56.14 (35.84)	54.12 (29.86)	37.61 (25.81)	29.60 (23.33)	29.22 (23.11)	28.68 (21.50)	29.73 (22.13)	9570/15,346
Hours of gaming per week	3.76 (4.55)	2.95 (4.59)	2.45 (4.19)	2.00 (3.56)	1.54 (2.84)	1.48 (2.70)	2.28 (3.96)	10,378/15,346
New language learning experience (%)	28	56	19	11	8	7	7	11,027/15,436
New musical instrument learning experience (%)	32	44	14	9	7	10	6	9687/15,346
Hours of reading per week	3.51 (3.85)	4.04 (4.801)	4.24 (4.37)	4.26 (4.21)	4.61 (4.20)	5.23 (4.44)	6.01 (5.14)	11,791/15,346
Hours of sleep	8.80 (2.02)	8.13 (1.63)	7.47 (1.38)	7.16 (1.20)	7.12 (1.12)	7.14 (1.13)	7.43 (1.31)	12,150/15,346
Hours of watching TV per week	6.84 (5.77)	6.57 (5.56)	7.17 (5.72)	7.39 (5.57)	7.10 (5.43)	7.96 (5.83)	8.54 (5.11)	12,047/15,346
Hours of web surfing	2.94 (5.12)	6.73 (6.15)	7.92 (6.10)	6.60 (5.52)	5.81 (5.21)	6.54 (5.01)	4.79 (4.82)	11,926/15,346

Note: Education level was specified as: 1 = less than high school, 2 = high school, 3 = some college, 4 = college degree and 5 = graduate degree or beyond. Exercise score was calculated using the formula specified in the Godin Leisure-Time Exercise Questionnaire: 3 $*$ (frequency of mild exercise) + 5 $*$ (frequency of moderate exercise) + 9 $*$ (frequency of strenuous exercise).

Table 2
Summary of *BrainBaseline* cognitive tasks and primary measures.

Cognitive construct	Task	*N*	Task description	Primary measure	References
Memory	Visual short-term memory task	2623	Delayed match-to-sample-task of four colored objects	Mean accuracy	Luck and Vogel (1997)
Memory	Spatial working memory task	3380	Delayed match-to-sample task of four spatial locations	Mean accuracy	Awh and Jonides (1998)
Memory	N-back task	3787	Indicate whether the current stimulus matches the one presented *n* steps earlier	2-Back condition mean accuracy	Kirchner (1958)
Processing speed	Simple reaction time task	5552	Respond as quickly as possible to the appearance of a target stimulus	Response time (RT)	Teichner (1954)
Processing speed	Go–No Go reaction time task	7409	Respond to a pre-defined target as quickly as possible but withhold response for distractors	Response time (RT)	Nosek and Banaji (2001)
Processing speed	Digit symbol substitution task	4395	Match symbols to their corresponding digits	Number of correct answers–incorrect answers	Golden, Espe-Pfeifer, and Wachsler-Felder (2000)
Attention (attention shifting)	Posner task	4474	View a spatial pre-cue followed by a target on the cued or un-cued location and indicate target feature as quickly as possible	Cost measured by invalid RT–valid RT	Posner (1980)
Attention (inhibition)	Flanker task	7263	Indicate direction of central target. Target is flanked by distractors, which are either in the same or opposite direction of the target	Cost measured by incompatible RT–compatible RT	Eriksen and Eriksen (1974)
Attention (inhibition)	Stroop task	4602	Respond to the color of the word and not its identity/spelling	Cost measured by incongruent RT–congruent RT	Stroop (1935)
Attention (focused serial attention)	Visual Search	3603	Search for a target defined by single feature or by a conjunction of features	Search slope of conjunction search	Treisman (1982)
Attention (divided)	Attentional blink task	8360	In a rapid serial visual presentation, identify first target and detect second target presence	Composite score measured by T1 accuracy – the size of blink (lag8–lag2)	Raymond, Shapiro, and Arnell (1992)
Attention (divided)	Trail Making	2998	Connect-the-dots or draw a line between targets in a specified ascending order	Cost measured by trail B RT–trail A RT	Reitan (1958)
Attention (divided)	Task Switch task	3170	Perform either high/low or odd/even judgment on a presented number. Background color indicates task to be performed	Switch cost (switch RT–non-switch RT)	Monsell (2003)

16.06, $p < .01$, and hours of web-surfing $F(5, 11822) = 62.81$, $p < .01$, and physical activity $F(5, 9483) = 246.60$, $p < .01$.

In general, new experiences such as learning a language or musical instrument declined with age. Less time spent on exercise and more time spent watching TV, reading books, and surfing web per week was also observed with increasing age, hinting at a trend towards a less active lifestyle.

3.2. Cross-sectional age effect

Participants had the option of performing the same task multiple times, but only results from the first attempt were used in the analysis. In order to examine cross-sectional age effects, we first performed a Principal Components Analysis (PCA) with orthogonal rotation (varimax) on the 13 cognitive tasks. We used the results from this analysis to form composite scores that corresponded to specific cognitive constructs. Two components had eigenvalues over Kaiser's criterion of 1 and in combination explained 59.20% of variance. The loadings of each task suggest that component 1 corresponded to processing speed (SRT, Go–No Go) while component 2 corresponded to memory (VSTM, SPWM, N-back). Attention tasks did not form a coherent factor. Given that attention is an umbrella term encompassing processes of orienting, engaging, disengaging, shifting, and inhibition (Vecera & Luck, 2002), it was not surprising to see no coherent construct from the different attention measures, as each was designed to tap a different aspect of attention. One measure (Visual Search) originally loaded with the memory construct, but was discarded from the analysis, since removing the measure improved the overall reliability of the memory construct. We also conducted Confirmatory Factor Analysis (CFA) with a three-factor model (processing speed, memory and attention). The CFA results did not provide an interpretable solution, either because of high correlations between processing speed and attention measures (>.9) or because of the low correlations between attention measures (<.3). Therefore, we performed the succeeding analyses using individual attention measures and composite scores from the two PCA components (processing speed and memory). Table 3 shows the final factor loadings after rotation and exclusion of the other tasks. We calculated the composite scores for processing speed and memory by summing the standardized z scores from each of the relevant tasks (coefficient >.4) with *equal* weight.

Table 4 shows the performance scores for each task across the 6 age groups. Fig. 1 shows the normalized scores of each composite score and attention measure across age groups. In all cognitive tasks, performance increased with age and was best during young adulthood (20 s). Performance gradually declined from the 30 s. In order to capture the bi-directional effects of age, we conducted two separate multiple regressions on each composite score and attention measure; one with the age range from 10 to 29 (increasing performance with age), and another with the age range from 30 to 90+ (decreasing performance with age). For the first multiple regression with the age range of 10–29, gender was included as a covariate. Education level was not included as a covariate in the younger age group since the age cohort and the level of education was directly related. For the second multiple regression with the older age range, gender and education level were included as covariates.

For the younger age group, there was a positive effect of age in most tasks except for Flanker, Trail Making and Task Switch. For the older age group, there was a negative effect of age in most tasks except for the Attentional Blink. The gender effect was significant in the memory composite score, processing speed composite score, and in the Posner, Stroop, Visual Search and digit-symbol substitution tasks. Males showed superior performance on the memory composite score, processing speed composite score, Posner, Stroop, and Visual Search tasks. Meanwhile, females performed better on the digit-symbol substitution task. Level of education was also a significant effect in the memory composite score, processing speed composite score, Flanker, and digit-symbol substitution tasks, with higher levels of education associated with better performance. In order to easily compare the age effects of each task, the standardized coefficients were presented in Table 5.

These results are consistent with the general findings of laboratory-conducted aging research. Following the rapid cognitive development in childhood, young adulthood (i.e., 20–39 year) is characterized by relative stability and peak cognitive performance. Afterward, the cognitive operations measured in this sample declined gradually with age, with older adulthood (60–90+) showing the most dramatic decline (Aartsen, Smits, van Tilburg, Knipscheer, & Deeg, 2002; Salthouse, 1998, 2009; Salthouse & Ferrer-Caja, 2003; Schaie, 2005). Furthermore, the present study expanded what is known about age-related cognitive change by demonstrating that the age effect is evident in various tasks tapping different cognitive operations such as memory, processing speed and attention, and is robust in a large and diverse study sample.

3.3. Processing speed hypothesis: mediation analyses

Next we examined if processing speed significantly mediates the relationship between age and cognition. That is, does controlling for processing speed reliably reduce the variance in cognition explained by age? To address this question, we conducted a mediation analysis (see Fig. 2). Mediation is a hypothesis about a relation among variables (Baron & Kenny, 1986; Judd & Kenny, 1981; MacKinnon, Fairchild, & Fritz, 2007), and three conditions must be met to conduct a Sobel test, which examines the presence of a significant mediation effect (Baron & Kenny, 1986; Sobel, 1982). First, the independent variable (age) must be associated with the dependent variable (memory composite score, and scores on attention measures). Secondly, the independent variable must be associated with the mediator variable (processing speed composite score). Finally, the mediator variable must be associated with the dependent variable.

In order to test the requirements of potential mediation, we examined the correlations between age, cognitive performance scores (memory composite score, and scores on attention measures), and processing speed composite score. As in the previous analysis, we conducted two separate analyses, one for participants aged 10–29 and another for participants aged 30–90+, since the direction of correlation between age and cognitive performance differed according to age group (positive correlation in the younger group, and negative correlation in the older age group).

In the younger age group, age was positively correlated with the memory composite score ($r = .175$, $p < .001$), and some attention measures ($r = .160$, $p < .001$; $r = .069$, $p = .002$; $r = .070$, $p = .008$; $r = .059$, $p < .001$, for Posner, Stroop, Visual Search, and AB, respectively). Age was also positively correlated with processing speed composite score ($r = .290$, $p < .001$). The processing speed composite score was positively correlated with the memory composite score ($r = .289$, $p < .01$), and all attention measures ($r = .054$, $p = .032$; $r = .129$, $p < .001$; $r = .097$, $p = .001$; $r = .122$, $p < .001$; $r = .100$, $p = .002$; $r = .107$, $p = .001$; $r = .094$, $p = .001$, for Flanker, Posner, Stroop, Trail Making, Visual Search, Task Switch, and AB respectively).

In the older age group, age was negatively correlated with memory composite score ($r = -.369$, $p < .001$), and other attention

Table 3
Summary of principal components analysis for the *BrainBaseline* games ($N = 1657$). In bold text are factor loadings > .40.

Game	Processing speed	Memory
SRT task (RT)	**.858**	−.040
Go–No Go task (RT)	**.778**	−.230
Visual short-term memory (accuracy)	.085	**.835**
Spatial short-term memory (accuracy)	−.351	**.544**
N-back (2-back accuracy)	−.232	**.622**
Eigenvalues	1.95	1.001
% of variance	39.18%	20.02%
Cronbach's alpha	.589	.476

Table 4
Group means of all cognitive tasks by age group. Standard deviations and the number of participants are in parentheses.

	10–19	20–29	30–39	40–49	50–59	60+
VSTM (accuracy)	79.36 (9.69, n = 237)	80.77 (8.24, n = 714)	79.13 (8.68, n = 606)	76.47 (8.48, n = 561)	73.87 (8.21, n = 352)	70.82 (9.30, n = 149)
SPWM (accuracy)	88.17 (10.67, n = 275)	91.08 (7.50, n = 892)	90.43 (7.74, n = 791)	88.85 (9.12, n = 725)	86.72 (9.95, n = 481)	84.16 (12.16, n = 207)
N-back (2-back accuracy)	71.88 (15.73, n = 360)	75.78 (13.18, n = 1042)	73.38 (14.19, n = 887)	71.83 (14.28, n = 824)	68.02 (15.97, n = 469)	66.07 (15.92, n = 200)
SRT (RT)	345.24 (59.41, n = 724)	324.34 (51.51, n = 1549)	321.94 (69.04, n = 1263)	327.83 (65.73, n = 1077)	337.04 (63.74, n = 639)	360.26 (110.12, n = 280)
Go–No Go (RT)	478.99 (79.14, n = 966)	454.97 (66.26, n = 2072)	466.44 (69.16, n = 1716)	482.18 (73.91, n = 1429)	508.68 (84.65, n = 819)	550.49 (93.90, n = 381)
Digit-symbol (# correct – incorrect)	36.60 (10.99, n = 580)	40.63 (11.36, n = 1213)	38.88 (12.30, n = 1039)	36.94 (12.57, n = 847)	32.51 (11.47, n = 454)	26.41 (12.46, n = 246)
Posner (cost)	34.39 (37.66, n = 444)	26.44 (31.88, n = 1206)	23.80 (34.13, n = 1039)	25.12 (36.50, n = 939)	26.59 (36.09, n = 568)	33.41 (39.52, n = 266)
Flanker (cost)	35.48 (51.97, n = 887)	33.88 (48.86, n = 2000)	34.95 (46.62, n = 1672)	35.91 (56.41, n = 1437)	38.96 (67.58, n = 843)	39.82 (72.60, n = 400)
Stroop (cost)	175.64 (119.96, n = 518)	169.58 (114.28, n = 1207)	176.82 (17.40, n = 1023)	192.29 (121.03, n = 952)	227.59 (154.66, n = 592)	244.39 (158.91, n = 293)
Attentional blink (composite)	.0373 (1.205, n = 862)	.1294 (1.15, n = 2327)	−.0443 (1.18, n = 2001)	−.0308 (1.22, n = 1752)	−.0415 (1.28, n = 977)	−.1256 (1.47, n = 420)
Visual Search (conjunction slope)	58.89 (31.16, n = 356)	55.60 (26.41, n = 958)	57.20 (25.36, n = 857)	63.38 (29.11, n = 762)	66.56 (28.11, n = 469)	70.25 (30.68, n = 189)
Trail Making (RT type B–A in seconds)	21.54 (38.68, n = 281)	22.33 (41.03, n = 826)	23.17 (51.23, n = 697)	29.27 (68.05, n = 631)	34.30 (69.68, n = 392)	133.40 (1077.66, n = 159)
Switch (cost)	197.90 (139.72, n = 269)	186.12 (132.45, n = 873)	187.22 (137.22, n = 724)	189.12 (155.13, n = 683)	216.71 (168.99, n = 436)	234.53 (152.87, n = 179)

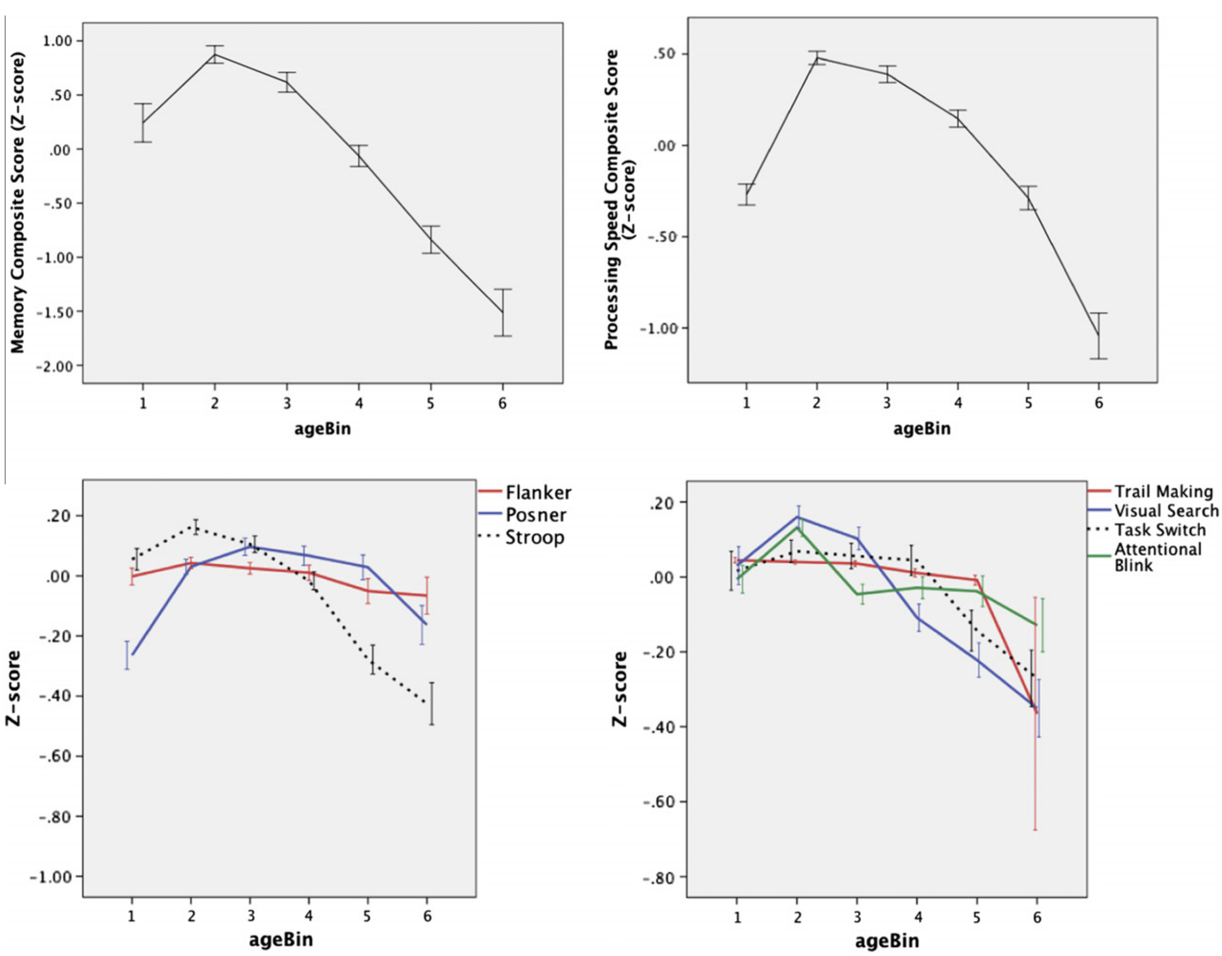

Fig. 1. The performance (z-score) of each cognitive measure across age. Error bars are standard errors ±1. The signs for Posner, Flanker, Stroop, Visual Search, Trail Making and Task Switch are reversed in order to be consistent with other tasks (positive values = better performance).

Table 5
Standardized coefficients for age effects after adjusting for gender in the younger group, and after adjusting for gender and education in the older age group.

Game	10–29		30–90+		
	Gender	Age	Education	Gender	Age
Memory composite score (n_younger = 574, n_older = 1078)	.083*	.169**	.091**	.036	−.365**
Processing speed composite score (n_younger = 1953, n_older = 2752)	.136**	.279**	.054**	.144**	−.270**
Digit-symbol substitution (n_younger = 2012, n_older = 2586)	−.125**	.309**	.093**	−.087**	−.293**
Posner task (n_younger = 1825, n_older = 2812)	.070**	.173**	.021	.094**	−.061**
Flanker task (n_younger = 3228, n_older = 4352)	.032^	.010	.044**	.016	−.029^
Stroop task (n_younger = 1966, n_older = 2860)	.069**	.064**	.022	.078**	−.170**
Attentional blink task (n_younger = 3519, n_older = 5150)	.027	.057**	−.015	−.021	−.012
Visual Search (n_younger = 1451 n_older = 2277)	.118**	.062*	.036^	.101**	−.149**
Trail Making (n_younger = 1252, n_older = 1876)	−.017	−.003	−.014	.023	−.067**
Task Switch task (n_younger = 1251, n_older = 2022)	.017	.008	−.041^	−.03	−.099**

Note: For gender, female is coded as 1 and male is coded as 2. The signs for Posner, Flanker, Stroop, Visual Search, Trail Making and Task Switch are reversed to be consistent with other tasks (more positive is better performance). A positive coefficient for age indicates better performance with increasing age. A positive coefficient for gender indicates better performance for males. A positive coefficient for education represents better performance with higher education.

* Significance is denoted by $p < .05$.
** Significance is denoted by $p < .01$.
^ Significance is denoted by $p < .10$.

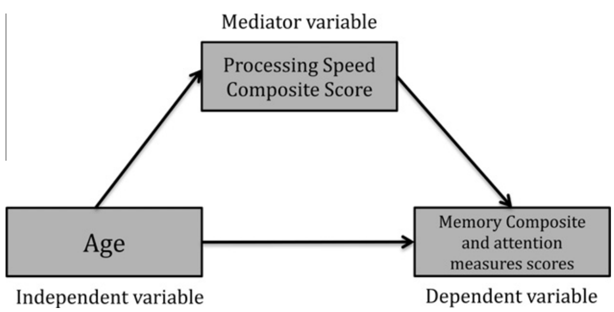

Fig. 2. Representation of the mediation model examined in our study. Processing speed mediated the relationship between age and memory and attention.

measures ($r = -.036$, $p = .016$; $r = -.059$, $p = .002$; $r = -.193$, $p < .001$; $r = -.059$, $p = .009$; $r = -.160$, $p < .001$; $r = -.085$, $p < .001$, for Flanker, Posner, Stroop, Trail Making, Visual Search, and Task Switch respectively), except for Attentional Blink. Age was also negatively correlated with processing speed composite score ($r = -.277$, $p < .001$). The processing speed composite score was positively correlated with the memory composite score ($r = .353$, $p < .001$), and some attention measures ($r = .046$, $p = .022$; $r = .074$, $p = .001$; $r = .158$, $p < .001$; $r = .185$, $p < .001$; $r = .088$, $p < .001$; $r = .045$, $p = .044$, for Flanker, Posner, Stroop, Visual Search, Task Switch, and Attentional Blink).

The mediation test was performed only on tasks that satisfied the requirement of significant correlations between independent and dependent variables, between independent and mediator variables and between mediator and dependent variables (younger age group: memory composite, Posner, Stroop, Visual Search, and Attentional Blink, older age group: memory composite, Flanker, Posner, Stroop, Visual Search, and Task Switch). We conducted two linear regression analyses to obtain raw regression coefficients and standard errors of the coefficients for the variables of interest. The first linear regression analysis was conducted to determine the association between the independent variable (age) and the mediator variable (processing speed composite score). A second linear regression was performed to examine the association between the mediator variable and the dependent variable (memory composite scores, and scores on attention measure), while adjusting for the independent variable (see Table 6 for results). For the younger age group, gender was included as a covariate while both gender and level of education were included as covariates for the older age group. Next, the regression coefficient and standard error of the coefficient for the relationship between the independent variable and the mediator variable as well as the regression coefficient and standard error of the coefficient for the relationship between the mediator variable and the dependent variable were entered into the Sobel test (Baron & Kenny, 1986; Sobel, 1982) to calculate the significance of mediation (http://www.danielsoper.com/statcalc/calc31.aspx). The Sobel test reached significance in all tasks except for the Flanker task for older adults where it was marginally significant at $p = .059$. Overall, the results suggest that the processing speed composite score mediated the relationship between age and other cognitive performance scores.

3.4. Processing speed hypothesis: multiple regressions

Although the above results suggest that processing speed mediated the relationship between age and a number of aspects of cognition, processing speed may not be the only explanatory mechanism that accounts for the age-related differences. In order to examine how well processing speed accounted for the cross-sectional age effect, we conducted multiple regressions on tasks showing significant mediation effects of processing speed. Age was entered as a predictor, with gender, education and processing speed composite score as covariates. If processing speed were the only explanatory mechanism that accounted for the age-related differences, factoring out processing speed in the relationship between age and cognitive performance would abolish the age-cognition relationship. As in the previous analyses, we conducted two separate multiple regressions, one for participants aged 10–29 and another for participants aged 30–90+.

Standardized coefficients for processing speed and age are presented in Table 7. Results showed that even after taking into account processing speed, the age effect in the memory component remained significant, with a positive age effect in the younger age group and a negative age effect in the older age group. The attention measures showed somewhat mixed results, showing that the age effect was attenuated in the younger age range for Stroop, Attentional Blink and Visual Search, but not for the older age group. In the older group, the age effect was attenuated only in the Flanker task.

3.5. Life-style influence: the interaction between exercise and age

It is well-known that moderate amounts of physical exercise has a positive effect on cognitive function in children and the elderly (Colcombe & Kramer, 2003; Voss et al., 2011 for review). However, to our knowledge, there is no study that has examined

Table 6
Shown are the results of the Sobel test for both age groups, along with the unstandardized coefficients and standard errors (SEs) for regressions with independent variable and mediator, and with mediator and dependent variable.

	10–29			30–90+		
	Independent and mediator, b (SE)	Mediator and dependent, b (SE)	Sobel test Z and one-tailed p	Independent and mediator, b (SE)	Mediator and dependent, b (SE)	Sobel test Z and one-tailed p
Memory composite	.075 (.006)	.321 (.054)	$Z = 5.36$, $p < .01$	−1.907 (.128)	.342 (.037)	$Z = -7.85$, $p < .01$
Posner task	.075 (.006)	.060 (.013)	$Z = 4.32$, $p < .01$	−1.907 (.128)	.031 (.014)	$Z = -2.19$, $p < .05$
Flanker task	NA	NA	NA	−1.907 (.128)	.022 (.014)	$Z = -1.56$, $p = .059$
Stroop task	.075 (.006)	.080 (.014)	$Z = 5.19$, $p < .01$	−1.907 (.128)	.066 (.015)	$Z = -4.21$, $p < .01$
Attentional blink task	.075 (.006)	.056 (.018)	$Z = 3.01$, $p < .01$	NA	NA	NA
Visual Search	.075 (.006)	.088 (.015)	$Z = 5.31$, $p < .01$	−1.907 (.128)	.087 (.016)	$Z = -5.10$, $p < .01$
Trail Making	NA	NA	NA	NA	NA	NA
Task Switch task	NA	NA	NA	−1.907 (.128)	.052 (.012)	$Z = -4.16$, $p < .01$

the exercise effect across a broader age range. To examine the association between exercise and cognitive function across the lifespan, we conducted an Analysis of Covariance (ANCOVA) on the processing speed composite score and memory composite score, and a Multivariate Analysis of Covariance (MANCOVA) on the attention measures (Posner, Flanker, and Stroop), with 5 age groups (20–29, 30–39, 40–49, 50–59, and 60+) and 2 exercise groups (high and low exercise group) as factors, and with gender and education as covariates. The teenage group (10–19) was not included in the analysis to minimize confounding the effects of rapid cognitive development. The exercise group was determined by the exercise score calculated by 3 ∗ (frequency of mild exercise per week) + 5 ∗ (frequency of moderate exercise per week) + 9 ∗ (frequency of strenuous exercise per week). Exercise scores ranged from 0 to 109. The mean was 36.45 with a 26.89 standard deviation and median of 31. We divided the exercise group into two groups, high exercise (score ⩾ 31) and low exercise (score < 31) groups. The age effect was significant in all analyses: for the processing speed composite $F(4,2566) = 44.88$, $p < .01$, memory composite $F(4,1027) = 35.92$, $p < .01$, and all attention measures $F(12,4365.78) = 6.51$, $p < .01$. In the following section, we only present the main effect of exercise group and the interaction between exercise group and age group for each cognitive composite or measure. The results are presented in Fig. 3.

3.5.1. Processing speed composite score

The main effect of exercise group was significant, $F(1,2566) = 6.83$, $p < .01$. The high exercise group showed better performance on processing speed tasks than the low exercise group. The interaction between age group and exercise group was not significant.

3.5.2. Memory composite score

The main effect of exercise group was not significant, $F(1,1027) = .176$, $p > .05$. The interaction between age group and exercise group was not significant, $F(4,1027) = .114$, $p > .05$.

3.5.3. Attention measures

The main effect of exercise group was not significant $F(3,1650) = .502$, $p > .05$. The interaction between age group and exercise group was not significant, $F(12,4365.78) = .992$, $p > .05$.

3.6. Life-style influence: the interaction between video game experience and age

Next, we examined the effect of video game experience on cognitive function. We performed an ANCOVA on processing speed and memory composite scores and a MANCOVA on attention measures (Posner, Flanker, and Stroop Tasks) using the same methods in the exercise analysis with game group (no-gamer, and gamer) instead of exercise group. The teenager group (10–19) was excluded from the analysis since education and the game experience were highly correlated with age. In all analyses, the age effect was significant: $F(4,2827) = 61.45$, $p < .01$ for processing speed composite score, $F(4,1133) = 40.09$, $p < .01$ for the memory composite score, and $F(12,4775.87) = 6.83$, $p < .01$ for the attention measures. In the following section we only present the main effects of game group and the interaction between game group and age group. The results are presented in Fig. 4.

3.6.1. Processing speed composite score

The main effect of game group was not significant, $F(1,2827) = 1.58$, $p > .05$. The interaction between age group and game group was not significant, $F(4,2827) = .758$, $p > .05$.

3.6.2. Memory composite score

The main effect of game group was not significant, $F(1,1133) = .212$, $p > .05$. The interaction between age group and game group was marginally significant, $F(4,1133) = 1.97$, $p = .09$. Planned comparisons revealed that the game effect was significant for age groups 20–29, 30–39 and 60+, but the direction of the effect was not the same across groups. In the younger age groups, gamers outperformed non-gamers, $t(347) = -2.28$, $p < .05$; $t(288) = -.1.86$, $p = .063$, for 20s and 30s respectively. However, in the older age group (60+), non-gamers showed marginally better performance than gamers, $t(62) = .189$, $p = .063$.

3.6.3. Attention measures

The main effect of game group was marginally significant $F(3,1805) = 2.35$, $p = .07$. The interaction between age group and game group was significant, $F(12,4775.87) = 2.22$, $p < .05$. Univariate analysis revealed that the main effect of game group was significant in the Flanker task, $F(1,1807) = 4.80$, $p < .05$, while the interaction was significant in the Flanker and Stroop tasks, $F(4,1807) = 3.40$, $F(4,1807) = 2.39$, $ps < .05$. In the Flanker task, the game effect was only significant in the older age group (60+), demonstrating that non-gamers showed better performance than gamers, $t(236) = 2.34$, $p < .05$. In the Stroop task, there was a trend for gamers to outperform non-gamers in the younger age group (30 ∼ 49), but non-gamers showed better performance than gamers in the older age group (50 ∼ 60+).

4. General discussion

The present study demonstrated the usability of a new mobile application as a data collection method by examining classic cognitive tasks and replicating the typical findings from a controlled laboratory setting. We used a set of cognitive tasks to examine

Table 7
Standardized coefficients for age effects after adjusting for gender and processing speed for the younger age group, and after adjusting for gender, education and processing speed for the older age group.

	10–29		30–90+	
	Processing speed	Age	Processing speed	Age
Memory composite (n_younger = 556, n_older = 1049)	.256**	.135**	.257**	−.291**
Posner task (n_younger = 1346, n_older = 2163)	.089**	.143**	.049*	−.056*
Flanker task (n_younger = 1607, n_older = 2399)	NA	NA	.042*	−.004
Stroop task (n_younger = 1245, n_older = 1976)	.075*	.040	.093**	−.167**
Attentional blink task (n_younger = 1222, n_older = 1968)	.069*	.057^	NA	NA
Visual Search (n_younger = 961, n_older = 1643)	.075*	.035	.136**	−.129**
Trail Making (n_younger = 894, n_older = 1488)	NA	NA	NA	NA
Task Switch Task (n_younger = 955, n_older = 1669)	NA	NA	.078**	−.065**

Note: The signs for Posner, Flanker, Stroop, Visual Search, Trail Making and Task Switch are reversed in order to be consistent with other tasks, where a positive coefficient for age represents better performance with increasing age. A positive coefficient for processing speed represents better performance with faster responses.
* Significance is denoted by $p < .05$.
** Significance is denoted by $p < .01$.
^ Significance is denoted by $p < .10$.

differences in cognition across the lifespan. Like previous studies, we found that cognitive function generally develops and peaks during young adulthood and gradually declines from the mid or late 30s (Salthouse, 2004; Salthouse, Pink, & Tucker-Drob, 2008). Although processing speed mediated the age-related variance in performance across tasks, it was not the only factor in cognitive differences as a function of age. After controlling for processing speed, the age effect remained significant for the memory construct and for some attention tasks.

Furthermore, the present study demonstrated the potential of mobile applications to expand the study of human cognition and to do so with large heterogeneous samples. We also examined the interaction between leisure activities (physical activity and video game experience) and age. Exercise showed a positive association with processing speed across the lifespan. Interestingly, contrary to some laboratory-based studies (e.g. Chaddock et al., 2010; Erickson et al., 2011) we did not find a significant relationship between exercise level and memory. However, there are at least two explanations for this. First, the previous studies obtained objective measures of fitness, rather than subjective or self-reported measures of exercise as in the present study. Second, it appears that not all aspects of memory benefit from exercise or fitness. Previous studies (Chaddock et al., 2010) have shown a relationship between fitness and relational but not item memory. This

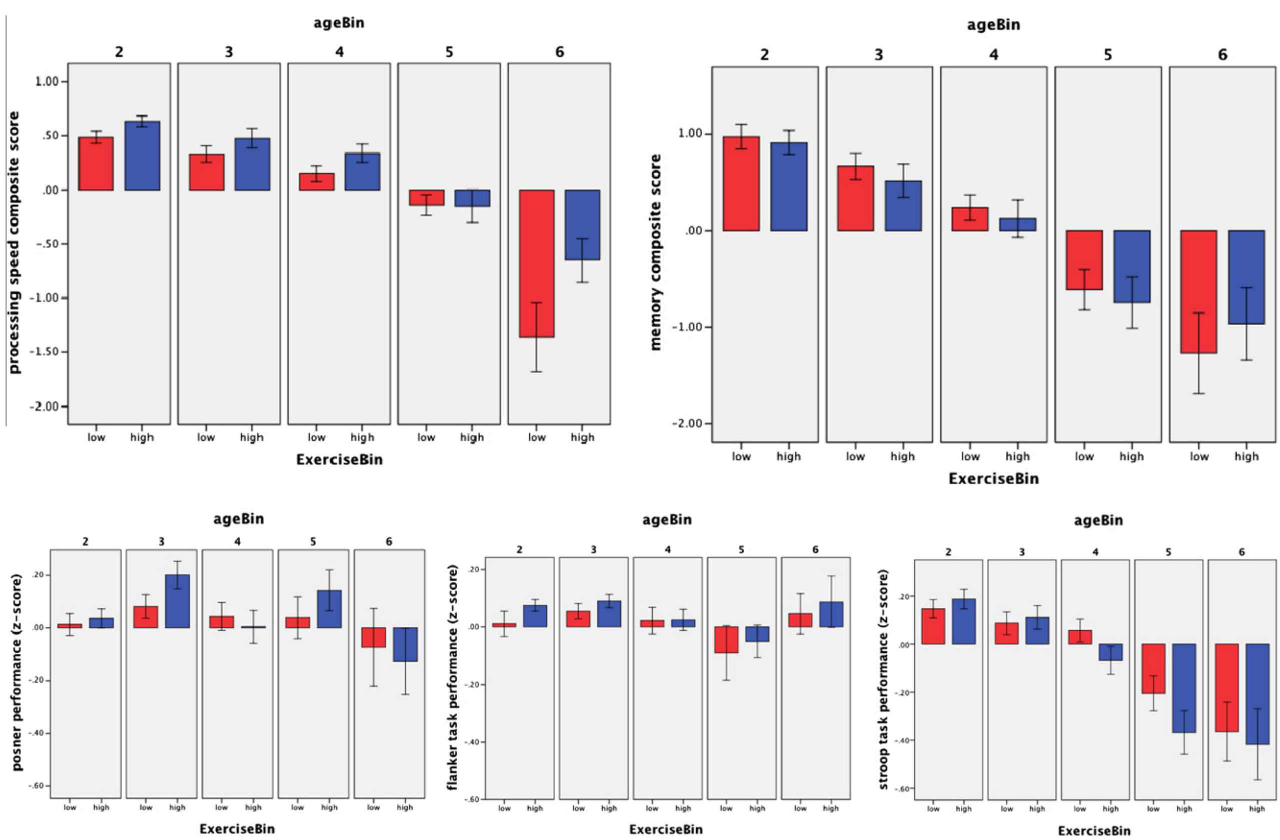

Fig. 3. Processing speed, memory and attention performance as a function of age group and exercise level. Error bars represent ±1 SE. Only participants who completed the exercise survey were included in the analysis. In each panel, the first bar represents the low exercise group, and the second bar represents the high exercise group. The signs for Processing speed composite score, Posner, Flanker, and Stroop tasks are reversed in order to be consistent with other tasks where more positive values indicate better performance. Age bins: 2 = 20–29, 3 = 30–39, 4 = 40–49, 5 = 50–59, and 6 = over 60.

potential specificity of memory-exercise relations can be further examined by the inclusion of a broader array of memory tests in revised mobile applications.

Video game experience showed opposite effects in younger and older adults. In younger adults, gamers tended to perform better on memory and attention tasks than non-gamers, while for older adults, non-gamers tended to outperform gamers. The bi-directional effect of video game experience on younger and older age groups can be interpreted in several ways. First, the opposite pattern might be induced by the cohort differences in life-long video game experience. It is reasonable to speculate that younger adult gamers have accumulated more experience with video games compared to the older adult gamers who may have only started to play video games in late adulthood, an activity that may have already been precipitated by poorer cognitive performance. Also, the type of video games played by younger and older adults may be different. Although the type of video game was not examined in the present study, it is likely that younger adults favor more fast-paced and complex video games than older adults. Considering that engaging in mentally stimulating or challenging activities has been shown to be beneficial for healthy cognition in older adults (Whitlock, McLaughlin, & Allaire, 2012), playing a less demanding genre of video games might not be very helpful. Finally, more video game play in older adults might also be related to a less active lifestyle. The correlation between hours of game play per week was positively correlated with hours of watching TV ($r = .164$, $p < .01$ and $r = .245$, $p < .01$ for 20s and over 60s respectively), hours of surfing the web ($r = .121$, $p < .01$ and $r = .232$, $p < .01$, for 20 s and over 60 s respectively) and hours of reading ($r = .084$, $p < .01$ and $r = .234$, $p < .01$ for 20 s and over 60 s respectively). Since physical activity has been shown to be important to cognitive function especially in old age, a sedentary lifestyle might instead be driving the negative association between gaming and cognitive performance in older adults.

The present mobile application-based study of age and lifestyle-related cognitive differences not only complements and confirms the previous findings of age-related cognitive change conducted in controlled experiment settings, but also expands our understanding of these phenomena by showing the effects in a large and diverse population, along with the influence of lifestyle factors such as physical exercise and video game experience.

4.1. Data collection in laboratory versus data collection with Internet/mobile application

Since most participants in laboratory studies are recruited using a subject pool typically composed of college students taking an introductory psychology course, or are recruited from within a university community, participant demographics are relatively homogenous in terms of age, education, social and cultural background. The homogeneity of participants can be a positive factor that reduces inter-participant variability. However, at the same time, it imposes the limitation of generalizing findings to the population. In contrast to a laboratory study, an application-based study has the potential to collect data across a wider age range, education level, and social and cultural backgrounds. Even with the possible age or socioeconomic status bias of a population with access to the Internet and such devices, the application-based study can potentially reach a more diverse population. The data collected from heterogeneous populations allows extending findings to the general population.

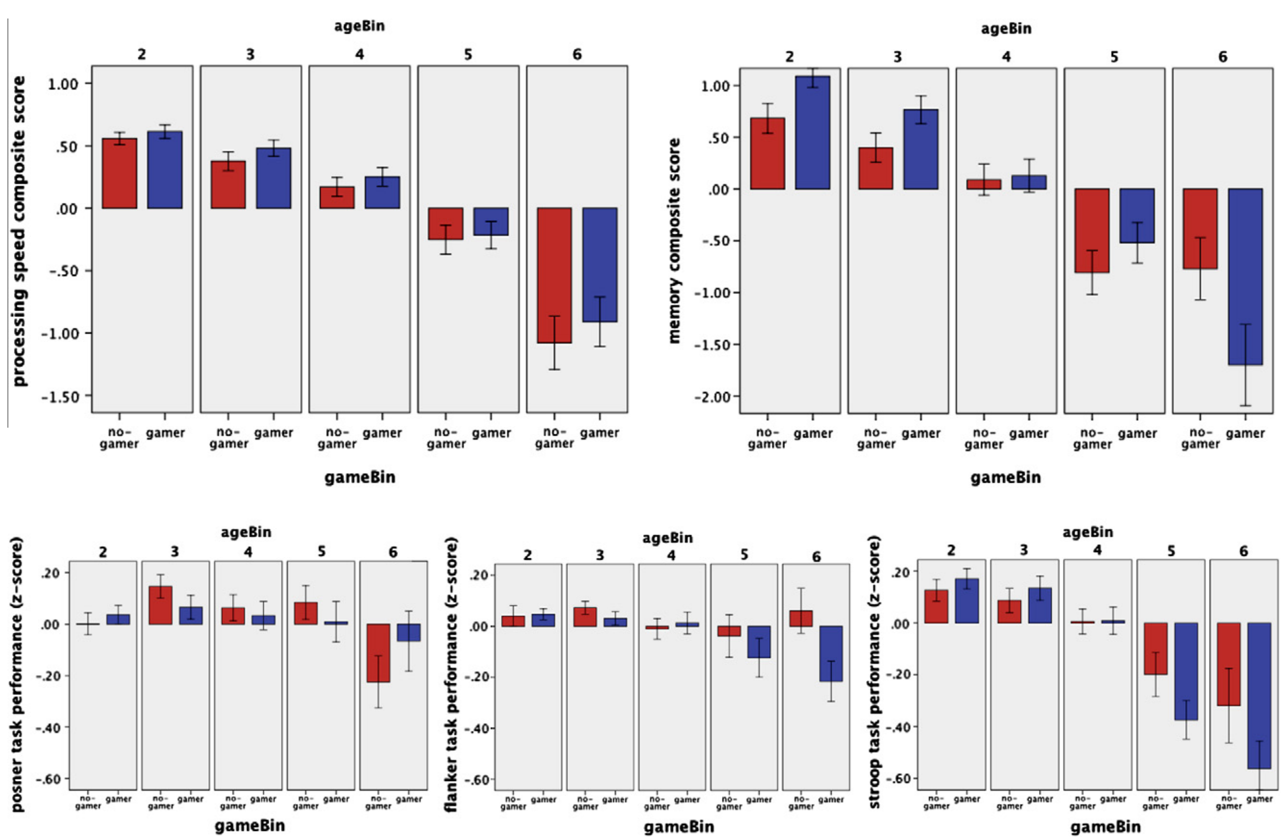

Fig. 4. Processing speed, memory and attention performance as a function of age and video game experience. Error bars represent ±1 SE. Only participants who completed the game survey were included in the analysis. In each panel, the first bar represents non-gamers, and the second bar represents gamers. Age bin 2 = 20–29, 3 = 30–39, 4 = 40–49, 5 = 50–59, and 6 = over 60. The signs for Posner, Flanker, and Stroop tasks are reversed in order to be consistent with other tasks.

One prominent disadvantage of an application-based study is the lack of control or ability to monitor participants' performance. While BrainBaseline recommends that users find a distraction-free setting in which to complete the tasks, participants may still perform the tasks in a noisy environment and not devote their full attention to the task (e.g. participants can perform the tasks while watching television, eating lunch, etc.). Also, because there was no obligation or guidance to complete the entire task battery of BrainBaseline, most participants completed only a subset of the tasks. As a consequence, there is likely to be variability and error, including non-response bias and higher dropout rates. Nonetheless, the large sample that can be obtained from such a study has the potential to compensate for the data power and quality lost by self-administration of the tasks, and the small number of trials contained in each task.

While it allows for minimal effort in data collection, an application-based study might require effortful labor and time to develop and implement the experiments of interest. Researchers without background knowledge in developing mobile applications may have to collaborate with software engineers. Therefore, it is important that researchers first consider the advantages and disadvantages of laboratory- and mobile application-based studies and determine which one is more suitable for their research. If the research requires a relatively homogenous sample of participants to undergo an experiment in a controlled setting, a laboratory study might be more suitable. Application-based studies might be more appropriate for large-scale cross-sectional or longitudinal studies that aim to assess the effects of training, treatments, or other information that a user can self-report.

4.2. Potential uses of mobile applications in studies of cognition

One of the most fundamental benefits of conducting an application-based study is that it allows researchers to conduct cross-sectional studies at low cost. Data collection is possible wherever the device is available, making it a useful tool for cross-cultural studies. The portability of the device also provides opportunities to gather data in regions or populations that may not be easily accessible or equipped with technology to handle extensive testing. Mobile applications can also be useful for cognitive or psychological assessment. The assessment tools can provide a basis for evaluating and defining individuals at high risk of cognitive impairment or disease. Participants' demographic information can also be used to estimate individual risk profiles. To do these individual-catered analyses, more trials would have to be programmed into each task, and the application will need to be administered in a relatively controlled setting. Nonetheless, the portability of the tool can make assessment more efficient.

Longitudinal training studies are far more costly to conduct in the laboratory and can also require more time and effort from the participants. Participants visit the laboratory regularly for weeks or months and this set-up can lead to higher dropout rates. The mobile applications can save multiple visits to laboratory, and can be easily administered in any setting. Researchers can investigate if the long-term monitoring and maintenance training broadly improves cognitive and social function, improves targeted cognitive, psychological or social functions, and if those training transfer to untrained tasks, particularly to performance outside of the laboratory setting.

5. Summary

In sum, mobile applications hold great promise as a data collection technique. The large number and diversity of participants and the low cost of the method is an ideal alternative for some psychological research questions. Issues such as unsupervised data collection can be addressed by adopting a system to monitor participants' performance and eliminate unreliable data. Mobile applications can have implications well beyond the laboratory, potentially helping researchers better understand the nature of human cognition by exploring the effects and interactions of various lifestyle, social and environmental factors.

Appendix A

A.1. Memory

A.1.1. Visual Short-Term Memory (VSTM) task

Each trial began with a one-second display containing four colored boxes randomly selected from seven possible colors (red RGB(1, 0, 0), green RGB(0, 1, 0), blue RGB(0, 0, 1), yellow RGB(1, 1, 0), purple RGB(0.88, 0.01, 0.89), black RGB(0, 0, 0), cyan RGB(0.02, 0.99, 0.78)). Each box measured 120 by 120 pixels and the boxes had a center-to-center distance of 210 pixels. Participants were asked to remember the colors of the boxes in this display. This memory display was followed by a blank fixation display for 1500 ms and then a test display containing a single colored box. On half of the trials, the color of the test box matched the color of one of the boxes presented in the memory display, and participants indicated whether or not the test color matched one of the memory items. Participants completed 10 practice trials, followed by 68 test trials. Overall accuracy was considered the primary measure of performance.

A.1.2. Spatial Working Memory Task (SPWM)

Each trial began with the presentation of a central fixation point for 1500 ms. Immediately following central fixation, 2 or 3 black dots with a radius of 11 pixels appeared on the screen for 500 ms, at locations that were pseudo-randomly determined on each trial. Participants were told to remember the location of each dot in the memory array. After a 1000 ms delay, a single red probe dot appeared at one location on the screen and participants were asked to determine whether or not the location of this red dot matched one of the locations occupied by one of the black dots in the memory array. On half of the trials, the red probe dot matched the location of one of the memory items. The probe dot remained on the screen for 2000 ms or until the participant responded. Participants completed 8 practice trials, followed by 60 test trials. Overall accuracy was considered the primary measure of performance.

A.1.3. N-back task

In this task, participants viewed a stream of numbers presented at fixation, and were asked whether or not the number presented on the current trial matched the number on the trial directly before it (1-back) or two trials before it (2-back). A 1-back condition block was followed by 2-back condition block. The stimuli consisted of a stream of centrally-presented black lower-case letters in 144 point Helvetica font, presented sequentially for 2000 ms with a lag of 1000 ms between each letter. Letters that appeared in the stream were chosen from A through *Z* with no exclusions. 20 were chosen randomly at each testing session, with the sequence pseudo-randomized for each block of trials. Participants responded using the match and no-match buttons on each side of the screen. In both 1- and 2-back conditions, participants performed 12 practice trials, followed by 20 test trials. Of primary interest was the mean memory accuracy in 2-back condition.

A.2. Processing speed

A.2.1. Simple Reaction Time Task (SRT)

In this task, participants were asked to respond as quickly as possible to the appearance of a target stimulus, which was a red circle with a radius of 35 pixels. The presentation of each target was followed by a variable delay period of 3000, 3500, 4000, 4500, 5000, 5500, 6000 ms before the presentation of the next target. No response after a 1500 ms delay, or premature responses (i.e., responses made prior to a target appearing) were counted as errors. Participants completed 7 practice trials followed by 21 test trials. Mean Response Time (RT) in correct trials was considered the primary measure of performance.

A.2.2. Go–No Go Reaction Time Task (Go–No Go)

In this task, participants responded to a centrally presented schematic happy or sad face with a radius of 35 pixels. Participants responded as quickly as possible with a button press for a happy face (go trials), but withheld their response for the sad face (no–go trials). The delay between faces was varied randomly (500, 640, 800, 950, 1100, 1250, 1400, 1550, 1700, and 1850 ms). 80% of total trials were go trials. Participants completed 10 practice trials followed by 50 test trials. Mean RT in correct go trials was considered the primary measure of performance.

A.2.3. Digit symbol substitution task

In this task, participants were asked to match symbols to their corresponding digits. Nine pairs of digit-symbols were presented on the top of the screen for reference. Digits with blank boxes were presented with a pool of symbols. For 60 s, participants filled the blank boxes with the corresponding symbols by dragging a symbol from the pool. Task performance was assessed by subtracting the number of incorrect trials from the number of correct trials.

A.3. Visual attention

A.3.1. Posner cueing test

At the beginning of each trial, participants were presented with a black fixation cross. After 500 ms, a small green (RGB(0, 1, 0)) precue, measuring 100 by 5 pixels, was presented on either the left or right side of the screen. After 100 ms, a target box measuring 120 by 100 pixels appeared on either the left or right side of the screen for 2000 ms or until a response was made. The target box contained a gap measuring 60 pixels in either the top or the bottom, and participants were asked to respond to the location of the gap as quickly and accurately as possible using the buttons on the left and right side of the screen. Critically, the target could appear at either the same location as the green pre-cue (valid cue) or at the opposite location (invalid cue). Participants completed 10 practice trials followed by 100 test trials. Task performance was assessed by observing the RT cost when the cue was invalid compared to valid.

A.3.2. Flanker task

At the beginning of each trial, participants were presented with a central fixation cross for 500 ms. Immediately following this, a flanker display consisting of 5 arrows measuring 66 by 40 pixels each with a spacing of approximately 17 pixels between each arrow, was presented for 2000 ms or until a response was made. On half of the trials, the flanking arrows (two on each side) pointed in the same direction as the target arrow (congruent) and on the other half they pointed in the opposite direction (incongruent). Participants were instructed to focus on the central arrow, and to report as quickly and accurately as possible whether this arrow pointed to the right or left. Participants completed 20 practice trials followed by 100 test trials. Task performance was assessed by observing the reaction time cost when flankers were incongruent compared to congruent.

A.3.3. Stroop Task

Each trial began with the presentation of a central fixation for 500 ms, followed by a colored word appearing at the center of the screen in 64 point Helvetica font. The word was displayed for 3000 ms or until a response was made. Participants were instructed to respond to the color of the word (not the word it spelled out) as quickly and accurately as possible using the buttons on each side of the screen. The compatibility between the identity of the word and its color was manipulated, yielding 24 compatible trials (e.g., the word red printed in the color red), 24 incompatible trials (e.g., the word red printed in the color blue) and 10 neutral trials (e.g., the non-color word printed in the color blue). Participants completed 13 practice trials followed by 58 test trials. Task performance was assessed by observing the reaction time cost when the ink color and word was incompatible compared to compatible.

A.3.4. Visual Search Task

In this task, participants searched an array of items for a prespecified target. Each trial began with a central fixation, presented for 1500 ms. Directly following this, an array of either 4 or 12 Landolt squares, measuring 50 by 50 pixels, appeared on the screen and remained onscreen for 5000 ms or until a response was made. Each square contained a gap of 30 pixels that appeared either on the top, bottom, left, or right side of the square. Targets were always a green box with a gap in the top or bottom, with the gap location appearing equiprobably. There were two search modes: feature and conjunction search. For the feature search trials, distractor items were all red, and participants searched for the target on the basis of its unique color (i.e., it is the only green item in the display). For conjunction search trials, distractor boxes were green and red, with all green distractors having gaps on the left and right, and red distractors having gaps in the top and bottom, Participants searched for the target based on the conjunction of color and gap location. For each type of search, there were two different set sizes, 4 and 12. Participants completed 5 trial practice trials for the feature search condition followed by two blocks of feature-search test trials (20 trials each), with one block containing 4-item displays and the other containing 12-item displays. Following the feature search blocks, participants completed 5 practice trials of the conjunction search condition, followed by two blocks of conjunction search test trials (20 trials each), with one block containing 4-item displays and the other containing 12-item displays. Of primary interest was the slope in conjunction search.

A.3.5. Attentional blink

The stimuli consisted of a centrally-presented stream of black capital letters in 144 point Helvetica font, each displayed for 50 ms with a lag of 50 ms between each letter. The letter stimuli were A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, Z. Each letter was presented only once on a given trial, and the order of presentation was determined randomly on each trial. On each trial, a pre-defined target letter (B, G, or S) was presented in red (RGB(1, 0, 0)) at position 10, 13 or 16 in the stream. On half of the trials, a black letter X (T2) was presented following the red target letter (T1), at a variable lag of 1–8 letters. Participants performed three separate practice blocks of three trials each. In the first, they were asked to monitor the stream for the red letter and report its identity (B, G, or S) on each trial. Following this practice block, participants completed a second practice block in which they were asked to search the stream for the letter X and report whether it was present or absent on each trial. Finally, participants performed a combined practice block in which they monitored the stream for both the identity of the red letter and the presence or absence of the letter X. Following these practice blocks, participants performed 45 test trials. Of primary interest was the composite score of the size of the "blink" observed and T1 accuracy. That is, the combination of z-score of blink, measured by difference between when the X was the second letter after the red target (when detection is typically worst) and when it was the 8th letter (when detection is typically good), and z-score of T1 accuracy.

A.3.6. Trail Making

This task required a subject to connect-the-dots or draw a line between targets in a specified ascending order. Two versions are available: A, in which the targets are all numbers (1, 2, 3, etc.), and B, in which the subject alternated between numbers and letters (1, A, 2, B, etc.). Participants were instructed to finish each task as quickly as possible. Task performance was assessed by cost measured by trail B RT–trail A RT.

A.3.7. Task Switch

Each trial began with the presentation of either a pink (RGB(1, 0.71, 0.76)) or blue (RGB(0.53, 0.81, 0.98)) background, inside of which was a number (1, 2, 3, 4, 6, 7, 8, or 9). Numbers were presented individually for 2500 ms. If the background was blue, participants reported as quickly as possible whether the letter was high or low (i.e., smaller or larger than 5) using one hand. If the background was pink, participants reported as quickly as possible whether the number was odd or even using another hand. Participants first completed a practice block of 12 trials of the "low/high" task, followed by a practice block of 12 trials of the "odd/even" task. Participants then performed another practice block of 12 trials in which the task to be performed switched unpredictably from trial to trial. Finally, participants completed 48 trials of test block in which the task switched unpredictably from trial to trial. Task performance was assessed by switch cost measured by switch RT–non-switch RT.

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