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Cognitive Diversity in a Healthy Aging Cohort: Cross-Domain Cognition in the Cam-CAN Project

Meredith A. Shafto, PhD[1], Richard N. Henson, PhD[2], Fiona E. Matthews, PhD[3], Jason R. Taylor, PhD[4], Tina Emery, BSc[2], Sharon Erzinclioglu, PhD[2], Claire Hanley, PhD[5], James B. Rowe, PhD[1,2,6], Rhodri Cusack, PhD[7], Andrew J. Calder, PhD[2], William D. Marslen-Wilson, PhD[1,2], John Duncan, PhD[2,8], Tim Dalgleish, PhD[2], Carol Brayne, PhD[1], Cam-CAN[9], and Lorraine K. Tyler, PhD[1]

Abstract

Objective: Studies of "healthy" cognitive aging often focus on a limited set of measures that decline with age. The current study argues that defining and supporting healthy cognition requires understanding diverse cognitive performance across the lifespan. **Method:** Data from the Cambridge Centre for Aging and Neuroscience (Cam-CAN) cohort was examined across a range of cognitive domains. Performance was related to lifestyle including education, social engagement, and enrichment activities. **Results:** Results indicate variable relationships between cognition and age (positive, negative, or no relationship). Principal components analysis indicated maintained cognitive diversity across the adult lifespan, and that cognition–lifestyle relationships differed by age and domain. **Discussion:** Our findings support a view of normal cognitive aging as a lifelong developmental process with diverse relationships between cognition, lifestyle, and age. This reinforces the need for large-scale studies of cognitive aging to include a wider range of both ages and cognitive tasks.

Keywords

healthy aging, cognitive function, principal components analysis, lifestyle, cognitive reserve

We all want to age healthily, and although a growing literature examines how we can achieve "successful" cognitive aging (Daffner, 2010; Depp, Harmell, & Vahia, 2011; Hartley et al., 2018; Saint Martin et al., 2017), there is no clear definition of what we mean by success. Frequently, large-scale studies of aging implicitly or explicitly define successful cognitive aging as the absence of age-related pathologies so that identifying or supporting success focuses on avoiding or reversing pathological cognitive declines in later life (e.g., Li et al., 2008). This approach provides little understanding of cognitive aging independent of pathology and decline; a better understanding of normal cognitive aging is important for changing our expectations and stereotypes about aging, for providing the basis for sound evidence-based policy development, and for developing targeted interventions to support lifelong cognitive health. The current study presents data from the Cambridge Centre for Ageing and Neuroscience project (Cam-CAN; www.cam-can.com), a study of healthy neurocognitive development across the adult lifespan. The Cam-CAN data set includes measures of general cognitive health and also includes a range of cognitive experiments which are sensitive to normal as opposed to pathological age-related changes. We report here on a wide range of

[1]University of Cambridge, UK
[2]MRC Cognition and Brain Sciences Unit, Cambridge, UK
[3]Newcastle University, Newcastle upon Tyne, UK
[4]The University of Manchester, UK
[5]Swansea University, UK
[6]Behavioural and Clinical Neuroscience Institute, Cambridge, UK
[7]Trinity College Dublin, Ireland
[8]University of Oxford, UK
[9]Cambridge Centre for Ageing and Neuroscience (Cam-CAN), UK

Corresponding Author:
Meredith A. Shafto, Department of Psychology, University of Cambridge, Cambridge CB2 3EB, UK.
Email: mshafto@gmail.com

cognitive measures extracted from the Cam-CAN data set and examine how diverse cognitive assessment in a cohort study improves our understanding of normal cognitive aging.

Many large-scale studies of cognitive aging either include only older participants (Deary, Gow, Pattie, & Starr, 2012; Ganguli et al., 2010; Gerstorf, Ram, Hoppmann, Willis, & Schaie, 2011; Kobayashi, Wardle, Wolf, & von Wagner, 2015; Miller et al., 2010; Saint Martin et al., 2017) or primarily assess cognitive domains that reliably decline with age, such as episodic memory or executive function (e.g., Bielak, Gerstorf, Anstey, & Luszcz, 2014; Deary et al., 2012; Lindenberger & Ghisletta, 2009; Salthouse, 2010b; Seeman et al., 2011; Singh-Manoux et al., 2012). The theoretical aim of these studies is often to identify commonalities across a range of cognitive processes that decline with age, to characterize a single or small number of "domain-general" factors underpinning age-related cognitive decline (Lindenberger & Ghisletta, 2009; Salthouse & Ferrer-Caja, 2003). This "single-factor" or domain-general approach is associated with the *dedifferentiation hypothesis* which posits that with increasing age, cognitive processes become more monolithic and less well-specified. This change is reflected in the predictions that age leads to increased intercorrelation between cognitive abilities (e.g., Hülür, Ram, Willis, Schaie, & Gerstorf, 2015), and an increase in the proportion of individual variation in cognitive performance that can be explained by domain-general processes (Hultsch, MacDonald, & Dixon, 2002; Lindenberger & Baltes, 1997; Lindenberger & Ghisletta, 2009; Wilson et al., 2002). The current study will examine whether a "single-factor" account is supported when including an atypically diverse set of cognitive measures and whether a domain-general factor accounts for more variance in older adults' performance compared with younger adults'.

In contrast to many large-scale studies, domain-specific experimental studies suggest that normal aging has a complex effect on cognitive function. First, there is ample evidence that the relationship between age and performance varies across cognitive domains (e.g., Park et al., 2002), with age-related decline seen in some domains such as fluid intelligence (Salthouse, 2009; Salthouse & Ferrer-Caja, 2003), whereas others are relatively preserved or even improve, including language comprehension, vocabulary and general knowledge (Burke & Shafto, 2008; Salthouse, 2009, 2010b; Salthouse & Ferrer-Caja, 2003; Thornton & Light, 2006; Verhaeghen, 2003). Second, even in domains where performance declines with age, impairments often reflect specific rather than general cognitive processes. This can be seen in the relationship of age to language function, where age is commonly found to impair aspects of language production such as word retrieval, while most core comprehension processes are preserved (Burke & Shafto, 2008; Shafto & Tyler, 2014). Moreover, although older adults have more word retrieval failures than younger adults, the age effect reflects a specific rather than general impairment in word production: While phonological access during production weakens with age, the underlying phonological representations remain intact (Burke, MacKay, Worthley, & Wade, 1991; Burke & Shafto, 2008; James & Burke, 2000), as do other production processes such as semantic access (Taylor & Burke, 2002). Finally, cognitive aging is a lifelong developmental process including both linear and nonlinear changes across the adult age range (Salthouse, 2009). Even abilities such as word retrieval that are reliably worse in older adults decline gradually across the adult lifespan, rather than when adults reach "old age" (Shafto, Burke, Stamatakis, Tam, & Tyler, 2007), a point raised across other domains by Salthouse (2009). Taken together, evidence from smaller scale experiments suggest that large-scale studies examining "healthy," "normal," or "successful" cognitive aging should (a) examine performance across the adult lifespan and (b) use a cross-domain range of cognitive measures that are (c) designed to identify specific mechanisms of normal age-related variance.

Current Study: Aims and Objectives

The current study builds on the findings of experimental cognitive aging research to ask whether we can demonstrate the same diversity within a cohort study and whether this benefits our understanding of normal cognitive aging. We employ the Cam-CAN data set, which combines general measures of cognitive health with domain-specific experiments that tap into normal rather than pathological variability (see Shafto et al., 2014, for a full description of the project protocol). The current study presents data from 21 cognitive tasks that (a) reflect a range of cognitive domains including memory, language, emotion processing, attention/executive function, face processing, motor/speed, and crystallized knowledge; (b) measure abilities that typically decline with age (e.g., episodic memory) as well as those that remain stable or improve across the lifespan (e.g., sentence comprehension); and (c) reflect both domain-general processes (e.g., fluid intelligence) and domain-specific processes (e.g., emotion regulation).

Our first aim is to examine the range of relationships between age and cognitive performance in the Cam-CAN data set, including 24 cognitive measures from 21 tasks across seven cognitive domains. Our second aim is to use principal components analysis (PCA) to summarize these age–cognition relationships across cognitive domains. We use PCA to strike a balance between maintaining as diverse a set of measures as possible while still providing summary measures that can reveal cross-domain components where they exist. Compared with other data reduction methods (such as latent variable analysis), PCA components reflect all sources of variance in the data (e.g., Costello & Osborne, 2005), but PCA can still test for whether underlying components reflect both domain-general and domain-specific processes which may differ or be equivalent across age groups. We use PCA across all participants, and also within sampling deciles, to test for the possibility that a dominant component will account for more variance in older than in younger adults (a prediction of the dedifferentiation hypothesis).

Our third aim is to ask whether an atypically diverse assessment of cognitive performance has relevance for understanding the relationships between lifestyle and cognition. In keeping with a pathological view of aging, previous studies of lifestyle measures have focused on later life and on how lifestyle choices help prevent or ameliorate cognitive decline (Clare et al., 2017; Marioni et al., 2012; Opdebeeck, Martyr, & Clare, 2016). There is less focus on cognition in younger or middle-aged adults and little attention to cognitive abilities that do not decline with age. The current study examines the relationship between cognitive performance and three lifestyle variables: education, social engagement, and enrichment activities (including both physical activity and other activities such as reading or pursuing hobbies). The relationship of these variables to cognitive function has been examined individually, and they are all related to the concept of *cognitive reserve*, the ability for older adults to be resilient to neural decline and maintain cognitive abilities (Chan et al., 2018; Chapko, McCormack, Black, Staff, & Murray, 2018; Clare et al., 2017; Valenzuela et al., 2012; Valenzuela & Sachdev, 2007). Previous research provides evidence for better cognitive outcomes in old age with higher education (Chapko et al., 2018; Clare et al., 2017; Marioni et al., 2012; Matthews, Marioni, & Brayne, 2012; Opdebeeck et al., 2016), higher levels of social engagement (Bielak et al., 2014; Bourassa, Memel, Woolverton, & Sbarra, 2017; Clare et al., 2017; B. D. James, Wilson, Barnes, & Bennett, 2011; Seeman et al., 2011), and higher levels of enrichment activities such as physical activity (Bielak et al., 2014; Clare et al., 2017), reading (Bielak et al., 2014; Clare et al., 2017), pursuing hobbies (Bielak et al., 2014), attending classes (Opdebeeck et al., 2016), or playing games (Clare et al., 2017; Jonaitis et al., 2013; Opdebeeck et al., 2016).

Although hypothesized contributors to cognitive reserve include measures from early adulthood (e.g., education) and midlife (e.g., occupational experience), studies often focus on cognitive outcomes in later life, that is, how cognitive reserve acquired throughout life affects late life cognition (Chan et al., 2018; Chapko et al., 2018; Valenzuela, Brayne, Sachdev, & Wilcock, 2011). To expand this approach to include cognitive performance in younger and middle-aged participants, we use lifestyle measures that reflect participants' *current* levels of social engagement and enrichment activities. However, we include a measure of educational attainment from early adulthood because education is a critical measure of cognitive reserve. Education often provides the most robust predictions of cognitive processing (Chapko et al., 2018; Opdebeeck et al., 2016), even being used as a standalone measure of cognitive reserve (Meng & D'Arcy, 2012; Valenzuela & Sachdev, 2006). Key questions in the current study include how the relationships between cognition and lifestyle may differ (a) across age groups, (b) between cognitive measures reflecting domain-general and domain-specific cognitive processes, and (c) between cognitive measures that decline or are maintained across the adult lifespan.

Method

Cam-CAN Project: Recruitment, Testing Stages, and Data Repository

In this study, we report a subset of the full Cam-CAN data set, so this section provides an overview of the project to contextualize the findings. The initial Cam-CAN data collection consisted of three stages: an interview (Stage 1) in which participants provided demographic, health and lifestyle, and core cognitive measures in person and via a self-completed questionnaire; detailed cognitive testing and core measures of brain structure and function (Stage 2) completed in testing sessions at the Medical Research Council Cognition and Brain Sciences Unit in Cambridge, UK (MRC-CBSU); and in-depth cognitive neuroscience tasks (Stage 3) also completed at the MRC-CBSU. Data reported here are taken from Stages 1 and 2.

Participants were recruited into Stage 1 from the Cambridge, UK community via their general practitioner (GP) surgeries. Green, Bennett, Brayne, Cam-CAN, and Matthews (2018) provide details about recruitment and exclusion, where out of 7,616 eligible participants who were initially approached, 2,680 (35.2%) were ultimately interviewed. Active refusals such as being too busy (61% of refusals; N = 3,008) and illness (35.6% of refusals; N = 1,756) made up the majority of refusals at this stage. Green et al. (2018) examined several factors affecting participation including gender, age, and deprivation. Key findings included no main effect of gender, evidence that middle-aged participants were more likely to volunteer than younger or older participants, and the finding that deprivation affected participation, especially in older adults.

Of the 2,680 participants interviewed at Stage 1, 709 went on to participate in Stage 2 (this stage had a planned number of 700). Recruitment into Stage 2 excluded participants with contraindications for magnetic resonance imaging (MRI), low Mini-Mental State Examination scores (MMSE; Folstein, Folstein, & McHugh, 1975; low scores were 24 or lower), poor hearing (failing to hear 35 dB at 1,000 Hz in either ear), poor vision (below 20/50 on the Snellen vision test; Snellen, 1862), poor English (non-native or non-bilingual English speakers), self-reported substance abuse, serious health conditions, or serious psychiatric conditions such as psychosis. Based on these exclusion criteria, 1,528 participants were ruled out of participation in Stage 2 during the Stage 1 interview via computer algorithm. A further 233 were excluded due to active refusal (N = 130), illness (N = 11), a change in circumstances such as moving from the area (N = 76), or having missing information (N = 16). Finally,

Table 1. Participant Sample Sizes, Gender Distribution, and Highest Educational Attainment by Sampling Decile.

	Decile							
	18-27	28-37	38-47	48-57	58-67	68-77	78-88	Total
Sample size	56	108	114	103	109	110	108	708
Gender (percent female per decile)	52	52	50	52	50	53	47	51
Education (percentage of total by category)								
No qualifications tried (under 16)	<1	1	<1	5	5	17	15	7
GCSE (age 16)	21	6	12	12	16	18	14	14
A-levels (age 18)	21	12	13	21	21	22	27	20
University (over 18)	57	81	75	62	58	43	44	60

Note. GCSE = The General Certificate of Secondary Education

210 participants did not move forward to Stage 2 because they were surplus to the sampling requirements (oversampled).

Further information about the recruitment, exclusion criteria, and contents of the testing stages can be found in Shafto et al. (2014), Taylor et al. (2017), and Green et al. (2018). Further details of exclusion and refusals in Stage 1 can be found in Green et al. (2018) and in Stages 2 and 3 can be found in Schweizer et al. (2019). Further details on the contents of the Cam-CAN data repository and information on how to access it can be found in Taylor et al. (2017) or at cam-can.com.

Participants. Participants were an $N = 708$ subgroup who completed detailed cognitive testing (Stage 2). Participants were recruited into Stage 2 equally across gender within seven sampling deciles (18-27, 28-37, 38-47, 48-57, 58-67, 68-77, 78+). Table 1 provides a summary of participant sample sizes, gender, and highest educational attainment across the deciles. Although age is used as a continuous variable in the main analyses, to improve interpretation of the results, some analyses and visualizations divide the group either into sampling deciles (1-7) or three broader age groups: a younger group including deciles 1-3 (R = 18-47, M = 35.13, N = 278), a middle-aged group including deciles 4-5 (R = 48-67, M = 57.62, N = 212), and an older group including deciles 6-7 (R = 68-88, M = 76.63, N = 218).

Materials

Cognitive tasks. All tasks reported here were either completed as part of an initial interview and questionnaire (Stage 1) or as part of subsequent cognitive testing sessions (Stage 2). The 21 cognitive tasks used in the current study are listed in full in Supplemental Table 1. The methodological details for most of these tasks are provided in Shafto et al. (2014) with the exception of the Spot the Word task, described by Baddeley, Emslie, and Nimmo-Smith (1993), and the "Story Memory" task which was taken from the logical memory test portion of the Wechsler Memory Scale–Third UK Edition (WMS-III UK; Wechsler, 1999). The 21 tasks reflect seven cognitive domains (Attention/Executive function, Language, Emotion processing, Memory, Motor/Speed, Face processing, and Crystallized Knowledge) and provide 53 variables overall (between 1 and 9 variables per task).

Six tasks across three cognitive domains were selected to represent processes typical of studies of cognitive aging where performance declines with age. These *Typically Declining* tasks are indicated in Supplemental Table 1 and consist of Fluid Intelligence, Choice Response Time (RT), and Verbal Fluency from the executive functions domain; Simple RT from the processing speed domain; and Visual Short Term Memory (VSTM) Capacity and Story Memory from the memory domain. While not inclusive of all tasks used in studies of single-factor or domain-general cognitive aging, these were chosen from the available data set as commonly used in large-scale studies of cognitive aging (e.g., Deary et al., 2012; Salthouse, 2009; Salthouse & Ferrer-Caja, 2003).

Lifestyle measures. Social engagement was assessed using three self-report questions about current social activities including how often participants (a) see their relatives, (b) attend clubs or social groups, and (c) see their neighbors. These questions were the same as those examined by Clare et al. (2017) and the questions and scoring strategy were similar to other previous studies (Ang, 2018; Bourassa et al., 2017; Clare et al., 2017). Each question was scored on a 3-point scale so that total scores ranged from 0 to 9. Current enrichment activities were assessed in a version of the Life Experience Questionnaire (LEQ; Valenzuela & Sachdev, 2007) which was modified for use on the Cam-CAN project. The LEQ asks participants about a broad range of life experiences, which include experiences from their current life, and for middle-aged and older adults, retrospective reporting of activities from previous life stages. On this questionnaire, enrichment activities are assessed in a subscale of the LEQ that queries seven aspects of recent life experience: (a) domestic and international travel, (b) outings to see family and friends, (c) reading, (d) playing musical instruments, (e) artistic pursuits, (f) speaking a second language, and (g) mild, moderate, and vigorous physical activities. Responses for each of these seven domains were scored on a 5-point scale so that enrichment activities scores ranged from 0 to 35.[1] The measure of education used was highest qualification achieved by standard exams, GSCE/GCE/CSE, A-levels, or university degree (see Table 1).

Procedure

Cognitive tasks. Participants completed the cognitive tasks during Stages 1 and 2 of the Cam-CAN project. All participants were offered all cognitive tasks with the following exceptions: Emotional Memory, Emotional Reactivity and Regulation, Motor Learning, and Force Matching. These tasks were only offered to half of the participants because versions of Emotional Memory and Emotional Reactivity and Regulation were included in Stage 3 of the project and participants could not repeat these tasks for methodological reasons. Participation in these tasks was counterbalanced across decile and gender groups, and tasks that were not offered to all participants are not included in PCAs.

Lifestyle measures. Responses for education and social engagement were given as part of the Stage 1 interview, which was conducted in the participant's home or another place of their choosing (such as their workplace). Responses for enrichment activities were collected from a questionnaire on lifestyle and health that participants completed prior to their interview which included the LEQ.

Analysis overview. We addressed our research aims in three analysis stages. (a) First, to establish the range of relationships between age and cognitive performance in the Cam-CAN data set, we conducted *within-task regressions* to examine the different relationships between age and 24 cognitive measures across seven cognitive domains. Given evidence for nonlinear age effects on cognitive performance (e.g., Salthouse, 2009), we included both linear and quadratic expressions of age in regression analyses. (b) Second, to provide a summary of these age–cognition relationships and test predictions of single-factor models, we conducted a *Cross-Domain PCA* using a subset of 17 measures (those that were offered to all participants) across the seven cognitive domains. We tested a key prediction of dedifferentiation by examining variance explained by the components in Cross-Domain PCAs within sampling deciles. We also compared the results of the Cross-Domain PCA with a *Typically Declining PCA* which included the six Typically Declining cognitive measures. (c) Finally, to examine how lifestyle relates to diverse cognitive assessment, we used regression to relate factor scores from the Cross-Domain and Typically Declining PCAs to lifestyle variables. These regressions included interaction terms with age, and significant interactions with age were followed up with regression analyses within younger, middle-aged, and older age groups to aid with interpretation. Analyses were conducted in SPSS version 25 (IBM, New York, USA).

Results

Cognitive Measures

A total of 53 variables from 21 tasks are summarized in Supplemental Table 1, with each task contributing between 1 and 9 dependent variables. For the 13 tasks with multiple dependent variables, we used PCA to create summary measures: Variables for these tasks were entered into PCAs, with separate PCAs used where tasks had substantively different stages or response instructions (e.g., separate summary measures were created for the Emotional Memory task "priming," "recognition," and "recall" variables). Factors with eigenvalues greater than 1 were used as cognitive measures for that task, and in all cases a single-factor solution was produced. All cognitive measures were standardized and the resulting 24 measures are listed in Supplemental Table 1 (see also Table 2). These cognitive measures were used in all subsequent analyses.

Within-Task Regressions: Age and Cognitive Measures

Results of regression analyses relating linear and nonlinear expressions of age to cognitive measures are presented in Table 2, and plots of the relationships between age and each cognitive measure are shown in Supplemental Figure 1. The results indicate a wide range of effect sizes (we used Cohen's F^2 and the conventional values of small effect =.02, medium effect = .15, large effect =.35) for effects of age (Cohen's F^2 = < .01-.79, median = .14) and age^2 (Cohen's F^2 = < .01-.85, median = .16). All of the Typically Declining measures revealed worse performance for older than for younger adults, including Fluid Intelligence, Verbal Fluency, Choice RT, VSTM Capacity, Story Memory, and Simple RT. Most measures were associated with a quadratic expression of age: although five measures showed evidence of only a linear relationship with age (Choice RT, Priming, Recall, Motor Learning, and Balance Test), a quadratic expression of age was significantly related to scores for 16 measures including two measures with the highest scores in middle age (Picture Naming and Familiar Faces).

Cross-Domain PCA

To provide a cross-domain summary of age–cognition relationships, 17 cognitive measures across seven cognitive domains (see Supplemental Table 1) were included in a Cross-Domain PCA using varimax rotation. We retained four factors which accounted for 51.42% of the total variance, based on having eigenvalues greater than 1 and confirmation using scree plots. The eigenvalues and variance explained by each factor as well as the loadings for each factor on the 17 measures are given in Supplemental Table 2.

Table 2. Results of Regressing Individual Cognitive Measures on Age (Model 1) and Both Age and Age^2 (Model 2).

		Model 1				Model 2					
Domain	Measures	Age	R^2	Cohen's F^2	F	Age	Age^2	R^2	Cohen's F^2	ΔR^2	ΔF
Attention/ Executive	Fluid Intelligence	–0.66****	.44	.79	508.20**	0.29	–0.96**	.46	.85	.02	27.83**
	Multitasking	–0.26**	.07	.08	46.54**	0.36	–0.63**	.08	.09	.01	6.89**
	Verbal Fluency	–0.29*	.08	.09	64.97**	0.95**	–1.25**	.12	.14	.04	31.48**
	Choice RT	–0.63**	.40	.67	436.89**	–0.27	–0.37	.40	.67	.003	3.82
Language	Picture Naming	–0.51**	.26	.35	200.16**	1.35**	–1.88**	.34	.52	.09	77.43**
	Tip of the tongue states (TOTs)	–0.31**	.10	.11	70.39**	0.78**	–1.11**	.13	.15	.03	21.72**
	Sentence Comprehension	0.02	<.01	<.01	0.22	–0.11	0.13	<.01	<.01	<.01	0.26
Emotion Processing	Emotion Recognition	–0.43**	.19	.23	151.29**	0.66**	–1.11**	.22	.28	.03	25.24**
	Emotion Reactivity	–0.30**	.09	.10	27.71**	0.66	–0.97**	.11	.12	.03	7.92**
	Emotion Reappraisal	0.01	<.01	<.01	0.01	–0.28	0.29	<.01	<.01	<.01	0.64
Memory	VSTM Capacity	–0.43**	.18	.22	146.06**	0.70**	–1.15**	.21	.28	.03	26.97**
	Story Memory	–0.37**	.14	.16	110.99**	0.36	–0.74**	.15	.18	.01	11.30**
	Priming	–0.22**	.05	.05	16.45**	–0.11	–0.12	.05	.05	<.01	0.11
	Recall	–0.57**	.32	.47	154.90**	0.04	–0.62*	.33	.49	.01	4.35*
	Recognition	–0.66**	.43	.75	246.31**	–0.22	–0.44	.44	.79	.01	2.66
Motor/Speed	Balance Test	–0.58**	.33	.49	331.06**	–0.60**	0.03	.33	.49	<.01	0.02
	Chair Rises	–0.35**	.12	.14	95.19**	0.30	–0.65**	.13	.15	.01	8.58**
	Simple RT	–0.35**	.12	.14	92.35**	0.15	–0.51*	.13	.15	.01	5.04*
	Force Matching	–0.08	.01	.01	1.85	0.51	–0.60	.02	.02	.01	2.96
	Motor Learning	–0.24**	.06	.06	18.76**	0.21	–0.45	.06	.06	.01	1.73
Face Processing	Unfamiliar Faces	–0.46**	.21	.27	175.49**	0.64**	–1.11**	.24	.32	.03	26.27**
	Familiar Faces	–0.33**	.11	.12	78.00**	2.19**	–2.55**	.26	.37	.16	143.44**
Crystallized Knowledge	Spot the Word	0.22**	.05	.05	36.50**	0.91**	–0.69**	.06	.06	.01	9.04**
	Proverbs	0.13**	.02	.02	11.65**	0.98**	–0.86**	.03	.04	.02	12.47**

Note. Standardized β values for expressions of age are reported, as well as explained variance (R^2), change in explained variance (ΔR^2, Model 2), effect sizes (Cohen's F^2) and F (Model 1) and ΔF (Model 2) values. The values of measures used in the regression models were aligned so that higher values represent better performance. RT = response time; VSTM = Visual Short Term Memory.
**$p < .05$. ****$p < .01$.

Factor 1 most strongly reflects the Fluid Intelligence measure, and the label of "Fluid Abilities" is applied because of this and because of the widespread loadings across a number of tasks requiring fluid abilities including VSTM Capacity and Verbal Fluency. Linear and quadratic expressions of age were related to factor scores, and as can be seen in Table 3 and Figure 1, the factor scores for the Fluid Abilities are lower for older ages.

Factor 2 loads on a number of tasks which require processing and naming of visually presented materials, including proper name production (Familiar Faces, Tip of the tongue states [TOTs]) and object naming (Picture Naming). This "Naming" factor is related to the quadratic expression of age (see Table 3) where the direction of the relationship between age and the factor score reverses after the third decile (see Figure 1). This reversal is reflected in a positive correlation between factor scores and age for participants under age 50 (r = .25, $p < .001$), but a negative correlation from age 50 and over (r = –.52, $p < .001$).

Factors 3 and 4 add little in interpretive power compared with their underlying measures as they load on only two (Factor 3) or one measure (Factor 4). Factor 3 clearly reflects Crystallized Abilities as measured by the Spot the Word and Proverb tasks, and Factor 4 simply provides a version of the Sentence Comprehension measure orthogonalized to the other factors and had an eigenvalue only slightly above 1 (1.19). The Crystallized Abilities factor is related positively to age (see Figure 1 and Table 3), and the Sentence Comprehension factor scores are unrelated to age. Although the sparse loadings on Factors 3 and 4 do not provide strong evidence about the underlying dimensionality of this data set, we retain these factor scores as useful summary measures reflecting the range of cognition–age relationships (see Supplemental Figure 1).[2]

Cross-Domain PCA by Decile

To examine evidence for age-related increases in the variance explained by the first principal component (a prediction of the dedifferentiation hypothesis), the Cross-Domain PCA was repeated within each decile, restricting the analysis to four factors so as to provide the best comparison with the PCA across all participants. Supplemental Table 4 presents the explained variance for each factor in each decile. There was

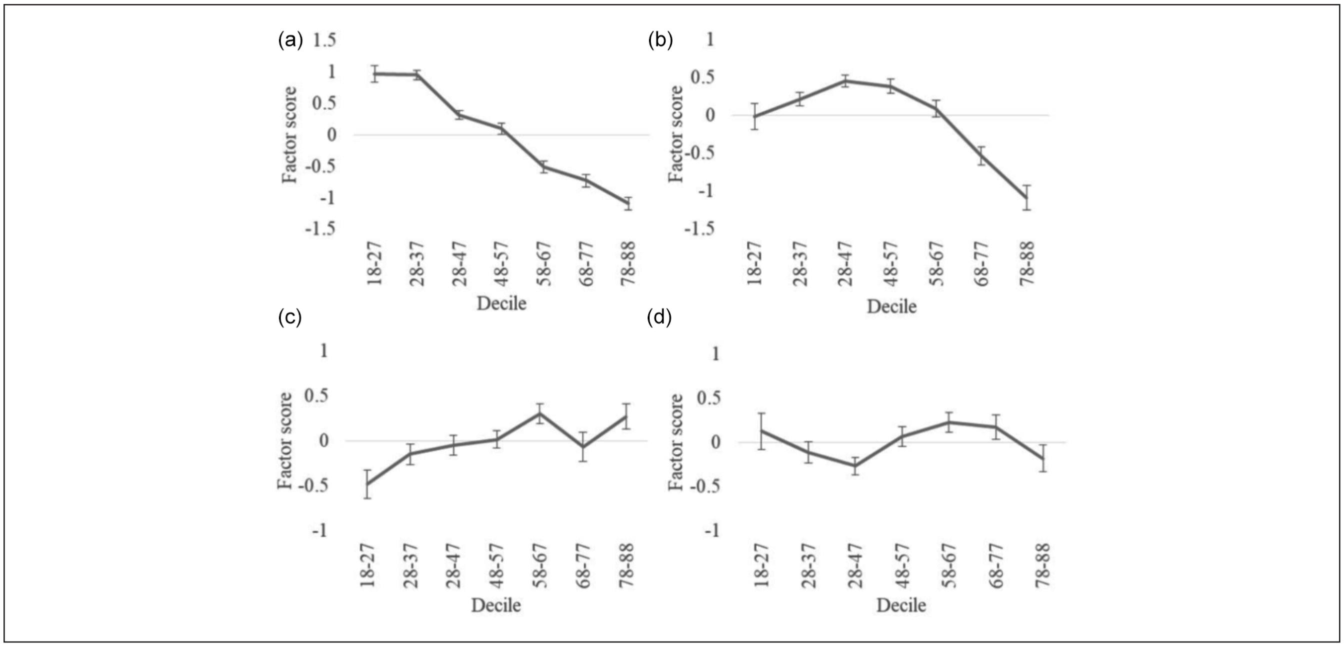

Figure 1. Cross-domain factor scores by sampling decile: (a) Factor l: Fluid Abilities; (b) Factor 2: Naming; (c) Factor 3: Crystallized Abilities; and (d) Factor 4: Sentence Comprehension.

Table 3. Results of Regressing Cross-Domain and Typically Declining Factor Scores on Age (Model 1) and Both Age and Age^2 (Model 2).

	Model 1			Model 2				
Factor	Age	R^2	F	Age	Age^2	R^2	ΔR^2	ΔF
Factor 1: Fluid Abilities	–0.70**	.49	416.02**	–0.61**	–0.09	.49	$<$.01	0.16
Factor 2: Naming	–0.35**	.12	60.77**	2.04**	–2.42**	.27	.14	84.75**
Factor 3: Crystallized Abilities	0.18**	.03	14.16**	0.52	–0.34	.04	$<$.01	1.30
Factor 4: Sentence Comprehension	0.05	$<$.01	1.13	0.20	–0.15	$<$.01	$<$.01	0.23
Typically Declining Factor	–0.68**	.46	489.96**	0.42*	–1.11**	.49	.03	34.22**

Note. Standardized β values for expressions of age are reported, as well as explained variance (R^2), change in explained variance (ΔR^2, Model 2), and F (Model 1) and ΔF (Model 2) values.
**$p < .05$. ****$p < .01$.

some variability across the deciles in the variance explained by each factor (Factor 1: R = 14.24%-17.89%; Factor 2: R = 10.22%-14.11%; Factor 3: R = 9.82%-12.93%; and Factor 4: R = 8.78%-12.01%), but there were no systematic relationships between variance explained and age groups.

Typically Declining PCA

For comparison with the Cross-Domain PCA, the Typically Declining PCA was conducted including only the six typically declining cognitive measures: Fluid Intelligence, Choice RT, Verbal Fluency, Simple RT, VSTM Capacity, and Story Memory. The results indicated one factor with an eigenvalue greater than 1, accounting for 48.43% of the total variance (see Supplemental Table 2 for details of the PCA).

Loadings were moderate to strong across all six input measures, with the strongest loading for Fluid Intelligence (.86). As can be seen in Table 3, the Typically Declining factor scores have a strong negative relationship with age. Finally, as with the Cross-Domain PCA, the Typically Declining PCA was repeated within each decile. Supplemental Table 4 provides the explained variance for the single-factor result in each decile, and as with the Cross-Domain PCA while there was some variability (R = 31.89%-39.18%), there was no systematic relationship with age.

Regressions Relating Lifestyle and Age to Cognition

The final set of analyses related cognitive factor scores to lifestyle measures, including (a) highest education attainment, (b) social engagement, and (c) enrichment activities. Supplemental Table 5 shows the correlations between these variables and age, demonstrating that the older age groups

Table 4. Results of Regressing Cross-Domain and Typically Declining Factor Scores on Lifestyle Measures With Age and Gender Covariates.

	Gender	Age	Education	Social engagement	Enrichment activities	Age × Education	Age × Social engagement	Age × Enrichment activities	R^2	*F*
Factor 1: Fluid Abilities	0.01	–0.63**	0.16**	–0.05	0.11**	<0.01	0.08*	–0.03	.58	56.54**
Factor 2: Naming	0.07	–0.39**	0.08	0.04	–0.07	–0.01	–0.21**	0.11*	.20	10.08**
Factor 3: Crystallized Abilities	0.01	0.38**	0.52**	–0.11*	0.08	0.14**	<0.01	–0.10*	.36	22.46**
Factor 4: Sentence Comprehension	0.20**	–0.04	–0.11	0.02	–0.08	0.11	0.01	0.05	.06	2.78†
Typically Declining factor	0.03	–0.61**	0.25**	–0.01	0.07	0.01	–0.03	–0.02	.57	70.45**

Note. Standardized β values are reported, as well as explained variance (R^2) and *F* values for each model.
**p* < .05; †*p* < .05, does not survive Bonferroni correction; ***p* < .01.

had lower education attainment ($r = –.25$, $p < .01$), higher social engagement ($r = .35$, $p < .01$), and lower levels of enrichment activities ($r = –.17$, $p < .01$). Among the lifestyle measures, levels of social engagement and enrichment activities are not correlated ($p > .10$), but higher education is associated with lower social engagement ($r = –.09$, $p < .05$) and higher enrichment activities ($r = .33$, $p < .01$). The relationship between education and social engagement does not survive in a partial correlation controlling for age ($r = .002$, $p = .95$), but even when age is controlled for, higher education is associated with higher levels of enrichment activities ($r = .30$, $p < .01$).

Lifestyle measures were entered into five regressions along with gender, age, and age interaction terms, predicting factor scores for each of the four Cross-Domain cognitive factors and the Typically Declining factor. In all regression models, continuous predictors were mean-centered to avoid multicollinearity and improve interpretation of interactions with age. To account for multiple tests, a Bonferroni correction was used so that we report regression analyses with *F* values significant at the $p < .05$ level and indicate where statistics did not survive correction (see Table 4). Evidence for interactions with age was followed up by repeating regression analyses within younger, middle-aged, and older age groups. To account for multiple tests, a Bonferroni correction was used so that we report regression analyses with *F* values significant at the $p < .05$ level that survived correction at a $p < .02$ level (see Supplemental Table 6).

Table 4 shows the results of regressions across all age groups, which indicate a range of relationships between cognitive factors and lifestyle measures. Factor scores for Fluid Abilities were higher for participants with higher education attainment and enrichment activities, regardless of age, whereas the relationship of Fluid Abilities to social engagement depended on age. To follow up the interaction of age and social engagement, the regression was repeated within younger, middle-aged, and older age groups. Results revealed that social engagement was negatively related to Fluid Abilities factor scores for young participants ($\beta = –.24$, $p < .01$), but not for middle-aged or older participants (middle-aged: $\beta = .01$, $p = .93$; older $\beta = .09$, $p = .39$; see Supplemental Table 6).

The regression with Naming factor scores revealed no main effects of lifestyle measures, but there were significant interactions of age with social engagement and enrichment activities. Follow-up regressions within age groups demonstrated that the effect of social engagement was numerically strongest for younger adults ($\beta = .14$, $p = .12$), weaker for middle-aged adults ($\beta = .11$, $p = .28$), and weakest for older adults ($\beta = –.07$, $p = .53$). The effect of enrichment activities did not reach significance within any age group either, but was numerically negative for younger adults ($\beta = –.09$, $p = .32$) and middle-aged adults ($\beta = –.04$, $p = .71$), and positive for older adults ($\beta = .05$, $p = .64$).

The Crystallized Abilities factor scores were higher for participants with higher educational attainment and social engagement, and there were also age interactions with educational attainment and enrichment activities. Within age group regressions indicated that higher educational attainment had a significant effect on the Crystallized Abilities factor scores for all age groups, but was strongest for older adults (young: $\beta = .31$,$p < .01$; middle-aged: $\beta = .47$, $p < .01$; older $\beta = .75$, $p < .01$). The effect of enrichment activities was only significant for younger participants ($\beta = .17$, $p < .05$).

The Sentence Comprehension factor scores were not significantly related to lifestyle factors, but was the only factor to demonstrate an effect of gender, with higher factor scores for females compared with males ($\beta = .20$, $p < .01$). However, the regression analysis was not significant when corrected for multiple tests (see Table 4).

Finally, the Typically Declining factor was only related to educational attainment, such that participants with higher factor scores had higher educational attainment, with no evidence of interactions with age.

Discussion

The current study provides an overview of normal cognitive performance across the adult lifespan and across multiple cognitive domains. Although a single-factor view was supported if using only a subset of typically declining measures, a Cross-Domain PCA identified both domain-general and domain-specific components, with factor scores that variably were lower, higher, or the same in older age groups. The Cross-Domain PCA repeated within sampling deciles did not support the dedifferentiation hypothesis prediction that a dominant component will account for more variance in older than in younger adults. This provides evidence that cognitive diversity is maintained across the lifespan, despite the decline in many of the cognitive measures (see also de Mooij, Henson, Waldorp, Kievit, & Kievit, 2018, for similar results from the Cam-CAN cohort). These results highlight the importance for large-scale studies of "healthy," "normal," or "successful" cognitive aging to recruit participants across the adult lifespan and include a range of cognitive measures that tap into normal as well as pathological variability.

Lifestyle Measures: Implications for Identifying Risks and Interventions

Evidence from the lifestyle measures suggests that there is variability in the specific relationships of lifestyle measures to cognitive factors scores: Education, social engagement, and enrichment activities had distinct relationships with the cognitive measures and differential interactions with age. Critically, lifestyle variables not only related to the domain-general Fluid Abilities factor but also related to three of the four Cross-Domain cognitive factors, including Crystallized Abilities, where scores improved across the adult lifespan. Likewise, lifestyle measures were not only related to cognitive performance in older adults, but in some cases the relationships were strongest for younger adults, or existed across age groups.

Educational attainment related robustly to Fluid Abilities and Crystallized Abilities, in keeping with previous evidence that higher education has a reliable effect on cognitive abilities, possibly stronger than other measures of cognitive reserve (Chapko et al., 2018; Opdebeeck et al., 2016). However, the relationship of cognition to education was not the same across the lifespan for all aspects of cognition; for example, education was most strongly related to Crystallized Abilities for older adults. Importantly, these interactions with age would be missed if we had focused only on the Typically Declining factor, where scores related to education but did not interact with age.

Although education predicted cognitive performance robustly, both social engagement and enrichment activities also demonstrated independent relationships to cognition, and again these would be missed with a focus only on the Typically Declining factor. Social engagement and enrichment activities have both been suggested as potential targets of interventions to support cognitive abilities in later life (Bielak et al., 2014; Bourassa et al., 2017; Clare et al., 2017; James et al., 2011; Marioni et al., 2014), with very few studies of aging including a younger group (but see Borgeest, Henson, Shafto, Samu, & Kievit, 2019; Seeman et al., 2011). The current results suggest that although social engagement relates to Crystallized Abilities across the lifespan, younger adults' cognition was most strongly related to social engagement for the Fluid Abilities and Naming factors. What is perhaps less expected is that increased social engagement is associated with *lower* factor scores in Crystallized Abilities and, for younger adults below age 40, lower factor scores for Fluid Abilities. These results suggest that higher levels of social engagement are not universally related to better cognitive performance in the current cohort. Thus, when considering risks for cognitive decline or potential interventions to support cognition, the type of cognitive process and time of life must both be considered. The relationship between cognition and lifestyle measures may depend not only on the nature of the cognitive processes and type of support but also upon the current level of cognitive processing and the relevance of different behaviors during different life stages.

Multidimensional Successful Cognitive Aging: Implications for Models and Interventions

The reported results support a more multidimensional view of normal cognitive aging than is typical of large-scale studies. The within-task regressions revealed relationships between performance and age that varied in both their strength and the nature of the effect. For example, and in keeping with previous findings, although Fluid Intelligence is lower for older adults than for younger adults (Salthouse, 2009; Salthouse & Ferrer-Caja, 2003), Sentence Comprehension scores do not differ across the age range (Tyler et al., 2010), and Spot the Word scores are higher for older adults than for younger adults (Salthouse & Ferrer-Caja, 2003; Verhaeghen, 2003). In keeping with the more targeted experiments included in the Cam-CAN project, age effects differed within domain as well; for example, in the Language domain, Picture Naming is lowest for older adults but Sentence Comprehension did not differ across the age groups.

The Cross-Domain PCA demonstrated that the Fluid Abilities factor explained the most variance and was markedly lower in old age (Lindenberger & Ghisletta, 2009; Salthouse & Ferrer-Caja, 2003). Although the strong relationship between age and the Fluid Abilities factor is in keeping with single-factor or domain-general accounts of aging, the diverse relationships between the other factors and age suggest that definitions of "healthy," "normal," or "successful" cognitive aging should not stop at the examination of typically declining or fluid abilities. Cognitive performance underpinned by the other factors (Naming, Crystallized Abilities, and Sentence Comprehension) did not decrease monotonically across age groups, but still represent critical everyday cognitive function. These and other processes should be accounted for in models of successful cognitive aging.

Similarly, when identifying markers or developing interventions to support cognition, results from the Cam-CAN cohort highlight the need for a lifespan, targeted approach that builds on strengths as well as seeking to ameliorate decline. First, lifestyle variables may relate differently to cognition across the lifespan: For example, Crystallized Abilities scores were related to enrichment activities only in younger adults. Second, lifestyle variables may relate to specific rather than general aspects of cognition: For example, neither social engagement nor enrichment activities related to the Typically Declining factor (but see Bielak et al., 2014; Clare et al., 2017; Seeman et al., 2011), but related to domain-specific processes (such as Naming). Similarly, although the effect of education interacted with age in relating to Crystallized Abilities, there was no age interaction in the relationship of education and Typically Declining factor scores, suggesting that age interactions with lifestyle measures may be missed if we only examine typically declining measures.

Limitations and Benefits of the Cam-CAN Data Set for Diverse Cognitive Assessment

The current study points to the need to develop more multidimensional, lifespan models of cognitive aging, to explore the specific relationships between lifestyle measures and cognition across the lifespan, and to develop better methods for characterizing cognitive diversity. The present results are limited in their ability to achieve these goals, both by the reported analyses (which use a fairly exploratory approach) and by limitations of the Cam-CAN data set itself. First, although Cam-CAN recruitment was population-based, it was not population-representative, and participants who completed full cognitive assessments were qualified to undergo cognitive neuroscience experiments including neuroimaging (see Shafto et al., 2014, for a description of participant selection for testing stages). As detailed in the "Method" section, Green et al. (2018) suggest that both age and deprivation may affect initial participation rates in Stage 1, although characteristics of participants who dropped out during Stage 2 have not yet been fully assessed.

Second, the Cam-CAN cohort is cross-sectional, with the attendant limitations on our ability to draw causal conclusions about the relationships between age, cognition, and lifestyle measures. Models of cognitive aging based on cognitive-behavioral experiments have relied heavily on cross-sectional data, resulting in an ongoing debate about the validity of longitudinal compared with cross-sectional evidence. Proponents of longitudinal approaches argue that cross-sectional data overestimate differences in performance across the age range (Nilsson, Sternäng, Rönnlund, & Nyberg, 2009; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Salthouse, 2009; Singh-Manoux et al., 2012), whereas proponents of cross-sectional studies argue that longitudinal use of targeted cognitive experiments is vulnerable to substantial practice effects (Salthouse, 2010a). In the current findings, cross-sectional measurement may particularly affect our understanding of the role of educational attainment, as cohort differences in education have been put forward as explaining the differences between cross-sectional and longitudinal findings (Rönnlund et al., 2005; Singh-Manoux et al., 2012). We cannot know what impact cohort differences in education had on the current results, but education did not merely serve as a proxy for age, as education had a variety of relationships to different cognitive factors across the age range. For example, increased education was strongly related to Crystallized Abilities, a cognitive measure which itself improved with age (while educational attainment declined); this finding highlights the complex role of education, not only as a proxy for cohort effects but also as an important reflection of cognitive reserve.

Although the Cam-CAN data set has limitations due to being cross-sectional, it serves as a complement to longitudinal data sets by providing features that are difficult to achieve longitudinally. First, although longitudinal studies of cognitive aging with younger or middle-aged participants are not unheard of (Singh-Manoux et al., 2012), practicalities mean studies more typically examine older people only (e.g., French, Sargent-Cox, & Luszcz, 2012; Lee, Chi, & Palinkas, 2019). Second, the range of measures available in the Cam-CAN data set would be difficult to acquire longitudinally. As previously noted, experimental cognitive data can be very vulnerable to practice effects, even with long delays between tests. Moreover, participants attended up to seven testing sessions to provide the range of cognitive and lifestyle measures reported here as well as the wealth of health, wellness, multimodel neuroimaging and cognitive neuroscience data available in the full data set. This breadth of testing would be unrealistic in a longitudinal study.

A final limitation of the current study is that, although the Cam-CAN data set uses an unusually diverse range of cognitive experiments, the factors that emerge from a PCA or related approach will depend on the variables included, and no single data set can be all-inclusive. Moreover, the current study used PCA as part of an exploratory approach, to provide a summary of the data, so we do not provide a more focused test of underlying factor structure (e.g., see Borgeest et al., 2019). Despite the limitations of any one data set, a picture of diverse cognitive aging can be developed if future cohort studies include more (a) domain-specific measures that are likely to reflect normal rather than pathological individual differences and (b) measures that have differential relationships to age rather than focusing on declines. Importantly, cohorts with diverse cognitive assessment such as in the Cam-CAN data set are also able to contribute to the understanding of domain-general function and cognitive factors that may be related to pathology in later life, as is evident from the domain-general Fluid Abilities and

Typically Declining factors. Indeed, this type of data set is amenable to identifying the effect of lifestyle choices on broad cognitive abilities that are common across the lifespan (Borgeest et al., 2019).

Conclusion

Developing models of successful cognitive aging should not be driven only by a focus on declines in cognitive health in late life, but should also include an examination of the whole adult lifespan and domain-specific processes that may be stable or improve with age. The Cam-CAN data set provides an important resource that supports the growing vision of cognitive aging as a lifelong developmental process with complex relationships across life stages and cognitive domains.

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ORCID iD

Meredith A. Shafto https://orcid.org/0000-0002-0016-2013

Supplemental Material

Supplemental material for this article is available online.

Notes

1. While the question about outings to see family and friends bears some similarity to social engagement questions, we included this question to retain the integrity of the LEQ subscale score; subsequent analyses revealed little correlation between the social engagement and enrichment activities measures (see the "Results" section and Supplemental Table 5).
2. Given the range of relationships between age and factor scores, we used confirmatory factor analysis (CFA) to verify that similar cognitive measures loaded on the same factors in young, middle-aged, and older age groups (configural invariance). The details of this analysis are provided in Supplemental Materials. We also used multigroup CFA to test for differences in factor loadings across age groups (measurement invariance; see Supplemental Materials and Supplemental Table 3 for results).

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