13

The Potential for Socially Integrated and Engaged Lifestyles to Support Cognitive Health With Aging

Precursors and Pathways

Elizabeth A. L. Stine-Morrow, Ted W. Worm, Aron K. Barbey, and Daniel G. Morrow

Relatively subtle declines in cognition, particularly for attention, executive control, speeded processing, memory, and apperception of abstract patterns, are normative with aging (Salthouse, 2012). Less benign are the profound changes in cognition that occur in the face of Alzheimer disease and related dementias (ADRD). With increasing longevities worldwide, the prevalence of AD has shown a marked increase in recent decades. In 2016, there were 43.8 million individuals diagnosed with AD, more than doubling the 20.2 million in 1990 (GBD 2016 Dementia Collaborators, 2019). In the United States alone, 5.8 million individuals were afflicted with AD in 2019 (Alzheimer's Association, 2019). The likelihood of AD increases with age: in the United States, only about 3% of adults aged 65 to 74 have AD, but almost a third of adults 85 years and older do. There is currently no cure. ADRD is typically preceded by a period of decline characterized as mild cognitive impairment (MCI; Gauthier et al., 2006; Jak et al., 2009; Petersen, 2011), but behavioral markers for ADRD may manifest much earlier in the lifespan (e.g., Snowdon et al., 1996). Risk factors as well are distributed across the life course (Livingston et al., 2017), suggesting that the development of ADRD is a lifelong process.

In the absence of a cure, there is some urgency to discover ways to reduce the risk and delay the onset of ADRD, with heightened interest in behavior-based pathways to resilience, characterized by the aphorism to "use it or lose it." Randomized clinical trials and animal models have offered relatively strong evidence for the protective effects of physical exercise on late-life cognition (Bherer et al., 2019; Kramer & Colcombe, 2018), though effects on delaying ADRD are mixed. Based on correlational and epidemiological work, there is now considerable evidence that a socially integrated and engaged lifestyle is related to longevity, resistance to AD, and late-life cognitive performance. Evidence for causal pathways is thin, but not entirely lacking. The purpose of this chapter is to consider the role of behavioral pathways for offsetting age-related cognitive declines and reducing the risk of ADRD, with a particular focus on activity engagement and social integration. Ultimately, science in this area should provide guidance for individuals, medical practitioners, and policymakers who are faced with decisions about lifestyle choices to optimize cognitive health through the lifespan. Thus, the

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litmus test of successful research in this area will be the ability to provide “prescriptions” for exactly what one has to “use” with accurate predictions of the cognitive function(s) that one will not “lose.”

In this chapter, we (a) provide an overview of the evidence for effects of active and socially integrated lifestyles on late-life cognitive health; (b) consider neurocognitive, socioemotional, and motivational mechanisms that may contribute to these effects; and (c) discuss the utility of an ecological approach to develop principles of lifespan health.

Effects of an Engaged Lifestyle on Cognition

Activity Engagement

Activity engagement is typically measured through retrospective self-reports of frequency via checklists or ratings. Activities are typically classified by type, based on factor analysis of frequency data or ratings of the quality of the activity (e.g., social, mental, physical) by the respondent, researchers, or an independent group. There is a sprawling literature relating such measures to cognitive outcomes, using both cross-sectional and longitudinal designs.

Among the earliest systematic investigations of this topic was a cross-sectional study by Christensen and MacKinnon (1993) in which activities in an hourly diary were classified by the researchers as passive (e.g., resting, reading, watching television) or active (e.g., domestic chores, visiting, gardening, writing). They found that the percentage of time in a day spent in active pursuits was related to fluid ability, but when they were weighted by ratings of social or mental stimulation, it was only mental engagement that predicted cognition, and only for the less well-educated segment of the sample; no effect of social engagement was detected. Generally speaking, cross-sectional relationships between activity engagement and cognition are often found; longitudinal data are more mixed. On the activity scale from the Victoria Longitudinal Study (VLS; Hultsch et al., 1993, 1999; Jopp & Hertzog, 2010), participants rate the frequency of engagement for specific activities over the last year on a 9-point scale (from “never” to “daily”). Classification of items by activity type (e.g., hobbies, novel information processing, social activities) has been validated with confirmatory factor analysis. Data from early waves (Hultsch et al., 1999) showed correlated change between activity engagement (in particular, novel information processing) and cognition. While establishing an intriguing connection between activity engagement and cognition, this early work left the direction of this effect uncertain: does activity engagement support cognitive health—or does cognitive health afford resources for maintaining an active lifestyle?

Prospective studies showing lagged correlations between engagement and later cognition (or cognitive change) are more suggestive. For example, in the PAQUID study (Fabrigoule et al., 1995), based on a representative sample of older adults in the Grionde region in southwestern France in which dementia was exclusionary at baseline, participation in 10 activities (e.g., sports, travel, reading) was found to reduce the probability of dementia 3 years later. Data from the Australian Longitudinal Study of Aging (Newson & Kemps, 2005) showed that, controlling for sensory function, activity engagement (measured as frequency of engagement over a 3-month period in 21 activities related to household maintenance and chores, social activities, and service) was predictive of change over a 6-year interval in speed, picture naming, and incidental recall (but not when education level was controlled). Using dual change score modeling with data from the Berlin Aging Study, Lövdén, Ghisletta, and Lindenberger (2005) reported that a 2-year change in activity participation was predictive of change in speed, while the reverse was not true.

An important innovation of the Kungsholmen Project (Karp et al., 2006; Wang et al., 2002, 2017) was an attempt to exclude those with even preclinical AD at baseline, thereby reducing the likelihood of reverse causation. Participants aged 75 years or older living in the Kungsholmen district of Stockholm were tested in 1987 and then every 3 years until 1996. Participants were selected at baseline for good cognitive health (i.e., no dementia diagnosis, Mini Mental Status Examination [MMSE] ≥23, not institutionalized), and those diagnosed with AD by the second time point were excluded from analysis (Wang et al., 2017). Thus, the risk for incident dementia from early-life and concurrent factors was estimated at the second follow-up under the assumption that cognitive health was maintained at least until the first follow-up. In an interview, participants provided their activities, which were then rated by the researchers (with validation by an independent group of older participants) for their physical, mental, and social demands. Higher ratings for these three components independently contributed to a reduced risk for AD diagnosis 3 years later, but the effects were larger when combined. Even controlling early-life education and complexity of work in midlife, activities involving mental and social complexity still predicted reduced AD risk.

Data from later waves of the VLS suggest that reductions in activity engagement may precede declines in some measures of cognition, which predict subsequent declines in activity engagement, particularly those involving social interaction (Small et al., 2012), suggesting reciprocal causation. In the Betula longitudinal data set out of Sweden, Mousavi-Nasab et al. (2012) showed that social activity (e.g., visiting) predicted level of episodic memory up to 10 years later, but not the reverse; however, episodic memory declines predicted declines in cognitive activity (e.g., reading books), but not the reverse. This pattern is consistent with the idea that social activity supported by sustained cognitive health stimulates cognitive activity.

Data from the Lothian Birth Cohort Study have shown that the relationship between socio-cognitive activity (a linear composite based on a principal component analysis of 15 activities; e.g., reading, visiting friends) and IQ at age 70 was reduced to nonsignificant levels when IQ at age 11 was controlled, suggesting that both activity and cognition in late life might derive from early-life intelligence (Gow et al., 2012)—or alternatively, that the ongoing relationship between activity and cognition is stimulated by early-life intelligence and its associated resources. Retrospective measures of activity engagement at midlife have been found to relate to level, but not change, in cognition (Gow et al., 2017), further suggesting that activity may be a marker for, rather than a cause of, cognitive health.

Similarly, in a coordinated analysis of cognitive and activity engagement data across four longitudinal studies (Origins of Variance in the Oldest-Old: Octogenarian Twins Study [Octo-Twin], the Long Beach Longitudinal Study [LBLS], the Seattle Longitudinal Study [SLS], and the Victoria Longitudinal Study [VLS]), Mitchell et al. (2012) found a consistent relationship between change in cognition and change in activity engagement, though activity at baseline did not predict change in cognition. Also, data from the longitudinal study of the Glostrup 1914 Cohort, a representative sample from this Copenhagen suburb, showed that while leisure activity (measured as a composite frequency rating of 18 leisure activities; e.g., family occasions, playing cards) was correlated with cognition (measured as Wechsler IQ), neither level of activity nor change in activity predicted change in cognition (Gow et al., 2014). Finally, based on a large-scale longitudinal study of residents drawn from electoral rolls around Canberra, Australia, Bielak et al. (2012) found activity engagement to be correlated with cognition but not predictive of change over 8 years.

Collectively, this body of literature suggests a fairly robust contemporaneous relationship between activity engagement and cognition. A predictive relationship between activity engagement and cognitive declines is more tenuous; some studies showing this relationship have used measures of activity engagement requiring active generation of the activities, raising the question as to whether the activities are protective against declines or whether it is cognitive demands of the activity assessment are simply serving as a proxy measure of prodromal AD. Measures of activity engagement that depend on ratings of frequency or difficulty vary widely in the items used. Generally, measurement is not grounded in a theory that might motivate the selection and grain size of the activities represented by items, or suggest how activities would be expected to cluster by frequency or difficulty. This is a scientific problem to be solved, one to which we return toward the end of this section.

Work

Work is a special case of activity engagement, which can provide external support to structure activities over years. Cognitive aging and work are intimately related (Fisher et al., 2017). There are a number of reports of longitudinal associations between engagement in work and cognition later in life (Schooler et al., 1999, 2004), as well as AD risk (Andel et al., 2005). Based on data from the VISAT study, a large-scale longitudinal study of workers, aged 32 to 62, in southern France, Marquié et al. (2010) found that, controlling for education and social activity at baseline, those with more stimulating work experience (e.g., measured as self-reports of mental effort and opportunities for further training) showed more growth memory, speed, and attention over the subsequent 10 years relative to those with lower levels of stimulation. Because people select into occupations, in part based on ability as well as temperaments related to ability, probing the causal link from work to cognition is challenging even in longitudinal data. Somewhat informative are studies that track cognition relative to the transition into retirement, in which the presumed mental stimulation of work is removed from one's routine. Such research (Lee et al., 2019; Xue et al., 2018) has provided some evidence that cognitive declines may be steeper postretirement. However, because decisions to retire could be influenced by subtle changes in cognitive health with prodromal AD, such findings are vulnerable to the interpretation of reverse causation.

"Natural experiments," in which cultural or political drivers of retirement afford individuals relatively less control over the retirement decision, may be especially informative. For example, countries with policies promoting early retirement show greater cross-sectional age differences in cognition from the early 50s to early 60s than those that do not (Rohwedder & Willis, 2010). In the United States, longitudinal data from the Health and Retirement Study (HRS) collected from 1998 to 2008, a historical period in which changes in Social Security policy created a "manipulation" so as to engender peaks in retirement at ages 62 or 65, precipitous declines in cognition were aligned at those points (Bonsang et al., 2012). A similar approach using comparable data from European countries, the Survey of Health, Aging, and Retirement in Europe (SHARE) also showed declines in cognition associated with exogenously determined retirement (Mazzonna & Peracchi, 2012). More generally, cross-national comparisons suggest that government policies that encourage work also support cognition. Bonsang et al. (2017) analyzed synchronized data across a set of national surveys (e.g., HRS, English Longitudinal Survey of Aging [ELSA]) to show a greater female advantage in memory performance for countries that showed higher level of endorsement for gender equality on the World Values Survey. Furthermore, this effect was shown to be mediated by educational attainment and workforce participation.

Plausible mechanisms underlying any causal relationship between work and late-life cognitive health are many, including mental stimulation, social stimulation, and structural support for organizing one's time and activities (e.g., regular schedules for meals and sleep). Two core mechanisms have been proposed relating to mental stimulation: complexity/mental demands/flexibility (Kohn & Schooler, 1978; Schooler et al., 1999, 2004) and novelty (Staudinger et al., 2016).

Some studies of job complexity capitalize on existing resources for characterizing jobs, including the Dictionary of Occupational Titles (DOT), which rates jobs according to their levels of complexity with people (e.g., mentoring, negotiating), data (e.g., analyzing, synthesizing), or things (e.g., precision work, operating equipment), and the US Department of Labor Occupational Information Network (O*NET) ratings of job-related mental work demands. Using data from the HRS, Fisher et al. (2014) examined the relationship between work complexity (measured as O*NET ratings) and cognition (episodic memory and the Telephone Interview for Cognitive Status). Those engaged in complex work showed higher levels of episodic memory prior to retirement and a subtle reduction in memory declines postretirement, as well as more shallow declines in cognitive status postretirement.

Studies based on data from the Swedish Adoption/Twin Study of Aging (SATSA) are useful here because Swedish retirement policies ensure that almost everyone has retired by the age of 65, when any age-related cognitive declines might be expected to be relatively modest (Schaie, 1994). Thus, age-related cognitive (and physical) declines are less likely to play a role in the retirement decision. Finkel et al. (2009) have reported that, controlling for education, job complexity in dealing with people (DOT) was predictive of verbal ability, spatial ability, and speed before retirement, and then a more precipitous decline postretirement. Also, from the SATSA, among twins who were discordant for dementia (and controlling for age, sex, and education), cognitive declines and AD risk were reduced by engagement with work that was complex with respect to interactions with people and data, but not with things (Andel et al., 2005).

In a cross-sectional study of autoworkers, Gajewski et al. (2010) compared age differences in response time, error rates, and electrophysiological response during task switching between those with routine (e.g., assembly workers) versus nonroutine (e.g., maintenance, service) jobs who were matched in education level. Older adults with routine jobs had especial difficulty in the more difficult task switch condition requiring memory-based cuing. There were also a number of distinctive features in the brain response that suggested difficulty with task preparation and error monitoring (though with such cross-sectional correlational data, these differences may well reflect selection effects).

Staudinger et al. (2016, 2020) have argued that novelty at work (e.g., learning new things, processing new information) may have salutary effects on cognition even among jobs that lack complexity. In support of this idea, Oltmanns et al. (2017) have shown that, relative to age- and education-matched controls, employees with more changes in tasks at work had higher performance on speed and working memory, as well as greater gray matter volume in the frontal-striatal network. More recently, Staudinger et al. (2020) developed a rating system for novelty processing at work (NPW) based on O*NET descriptors. They reported an analysis of HRS data showing that, controlling for job complexity, NPW buffered cognitive declines across 14 years.

As a form of activity engagement that both is normative for adults and shows wide variation in cognitive and social demands (which may to some extent be characterized by existing formal systems, such as O*NET), work provides an interesting laboratory for the study of lifestyle effects on cognitive aging. This body of research is suggestive of beneficial effects; however, novelty, complexity, and social demands are very typically interwoven, so that the mechanisms underlying work-related benefits are very much an open area for investigation.

Social Integration and Isolation

In the broader literature on activity engagement, the effects of activity per se are often difficult to tease apart from those of social interactions, as activities frequently involve other people. Following Fratiglioni et al. (2004), we adopt the broad term *social integration*, though this construct is operationalized in myriad ways. A recent meta-analysis of prospective longitudinal studies (Evans et al., 2019) suggests that low levels of social isolation, measured as more social activities and larger social networks, are related to better late-life cognition. There was large heterogeneity in effect size, but this finding seemed to hold regardless of whether social isolation was measured in terms of activity or networks.

Measurement of social relationships reflects an array of interrelated constructs (Berkman et al., 2000), including the size and quality of the social network (e.g., the number of close and distal ties, frequency of interaction), social support and social provisions (e.g., the availability of people on which to rely), attachment (e.g., feelings of connectedness), and loneliness (e.g., feelings of isolation), which plausibly reflect different sets of mechanisms through which social integration may impact cognition. Properties of social networks have been shown to be related to cognition and health (Fratiglioni et al., 2004). For example, in the PAQUID study, never-married (but not widowed or divorced) individuals were at greater risk for AD relative to married individuals (Helmer et al., 1999). Longitudinal data from the Betula study showed that, controlling for age, education, and leisure activities, married couples showed less decline in episodic memory over 5 years relative to their single or widowed counterparts (Mousavi-Nasab et al., 2012). Also, marital quality is predictive of health and mortality (Robles et al., 2014). Married couples in the Seattle Longitudinal Study showed significant correlations between cognitive performance at baseline and became more similar over time (Gruber-Baldini et al., 1995). Based on a meta-analysis of prospective longitudinal studies, Kuiper et al. (2015) concluded that lower frequency of social participation and social contact, as well as loneliness, increased the risk for dementia risk, but that smaller social network size did not. Collectively, these data suggest that it may be that it is significant close relationships that matter for cognitive health, rather than simply social exposure.

A well-developed literature with both animal and human models (Cacioppo et al., 2015; Ong et al., 2016) shows robust effects of loneliness and isolation on health. Animal models in which social isolation can be manipulated have been exploited to establish causal pathways, showing that acute and sustained social isolation can act as a stressor, which can have deleterious effects on health, and thereby cognition. There is robust debate as to whether objective isolation versus perceived isolation (e.g., loneliness) has the stronger effects on health. Data from the Rush Memory and Aging Project suggest that it the experience of loneliness that is a significant dementia risk, rather than objective social isolation (Wilson et al., 2007). Generally, there is solid evidence for a relationship between loneliness and cognitive declines with aging (Cacioppo & Hawkley, 2009).

Experimental Approaches

Lifestyle interventions combining activity engagement, social integration, and worklike elements, while limited in isolating mechanisms, have the advantage of experiments in testing the causal account. In the Experience Corps project (Carlson et al., 2009, 2015; Fried et al., 2013), older adults were randomly assigned to a program in which participants served as support staff in Baltimore city schools or to a low-activity control. Differential increases for the former group in executive control measures, as well as cortical and hippocampal volume, have been reported. In the Synapse project (Park et al., 2014), older adults learned new skills—quilting, digital photography, or both (dual-training). Relative to a placebo control that did home-based activities, including puzzles and listening to music, the photography and dual-training groups selectively improved in episodic memory, and the dual-training group improved in speed of processing. In the Senior Odyssey project (Stine-Morrow et al., 2014), older adults were randomly assigned to engagement in a team-based competition in creative problem-solving or to a reasoning training control. Those in the control group showed selective improvement in reasoning (as expected), while those who engaged in the creative problem-solving group showed selective improvement in divergent thinking, which is a critical skill in creative problem-solving. Collectively, these interventions provide experimental evidence for the idea that core abilities can be shaped by lifestyle. However, the inconsistent mapping of selective (neuro)cognitive gains onto program components does not obviously suggest general principles of how activity engagement impacts cognition.

So What Conclusions Can We Draw?

Does existing evidence support the aphorism "use it or lose it"? Prospective relationships of social and activity engagement with cognition and health are often, but not consistently, found. Interventions are suggestive of causal effects, but the selective nature of these effects is unsystematic. There are many barriers to interpreting existing findings.

Measurement. Measures of engagement are diverse. A key barrier to progress is the relative dearth of theory to guide the measurement of activity engagement, which is largely based on intuitive understandings of dubious validity that are not grounded in established psychological or neurological constructs (e.g., reading is considered "active"/"effortful" in some studies but "passive" in others; distinctions between crafts vs. games or travel vs. experiential development lack rationale in terms of underlying mechanisms). Furthermore, measures of cognition, although typically psychometrically sound, are also diverse and, importantly, may or may not reflect elements of cognition that are sensitive to context-specific enrichment. Collectively, such data do not easily lend themselves to isolating either the properties of beneficial lifestyles or their outcomes.

Another challenge of measurement is the almost exclusive reliance on retrospective self-reports of engagement. For example, intact cognition may enable people to recollect their daily activities and social interactions in greater detail, so that relationships of cognition with engagement may reflect a bias in reporting. A related possibility is that engagement and social integration reflect part of the self-schema or narrative of bright people (Cross & Markus, 1994), in which case the relationship of cognition with lifestyle may again reflect a report bias (Brenner & DeLamater, 2016). In fact, the internal consistency of older adults' reports of activity engagement from the age of 6 to the present is astonishingly high (e.g., $\alpha = .88$; Wilson et al., 2003). It seems more likely that this reflects coherence of identity rather than consistency in, for example, engagement in playing card games over the life course (cf. Salthouse, 2006).

Interpretive Ambiguity of Differences in Change. The seemingly most straightforward result to support the benefits of some form of cognitive or social engagement would be a preserved or positive trending change in longitudinal measures of cognitive functioning. However, in the absence of information about the broader lifespan context, this might be misleading. There is now considerable evidence that preserved cognitive functioning associated with privilege early in the lifespan tends to be associated with a compression of morbidity (Fries, 1980), a longer period of intact function with a more precipitous drop later (e.g., Stern, 2009). Thus, conditions that are in actuality favorable to cognition during early- to mid-old age are likely to produce steeper declines at life's end. Such a pattern can make it difficult to detect positive effects of engagement, especially later in the lifespan—and of course, the timing of measurements relative to the full lifespan of an individual is rarely available.

Overzealous Use of Covariate Analysis. The relationship between engagement and cognitive decline can be reduced, sometimes to nonsignificant levels, when educational level, IQ, and/or socioeconomic status (SES) are controlled (Newson & Kemps, 2005). There are innumerable reasons that individuals with favorable backgrounds may show reduced cognitive declines (e.g., better health care, food security, reduced stressors), and taken at face value, it is quite a reasonable analytic strategy to control baseline values in an effort to isolate the effects of engagement on cognitive aging. However, it is also the case that these early-life indicators, especially education, may stimulate a complex cascade of events that can predispose one to late-life cognitive health—including a skill set for managing everyday behavior. Treating them as nuisance variables to be controlled may cause us to miss the very phenomena in which we are interested.

Reverse Causation. When relationships between engagement and cognition do manifest in the data, the causal chain may operate in the other direction. Those with intact cognition may be better able to manage and cultivate an active lifestyle rich in social interaction, so that cognitive declines may stimulate declines in activities and social networks. Those in poor health and/or experiencing cognitive declines may have difficulty sustaining relationships. The increasing availability of longitudinal data allowing for the examination of the prospective relationship between early-life engagement and later cognition provides better evidence for causal connections, relative to cross-sectional data. However, patterns of engagement and cognition tend to show some reliability over time, so that reverse causation is often an alternative explanation even in prospective studies.

The preclinical phase of AD has been characterized in terms of declines in both episodic (e.g., memory for word lists) and semantic (e.g., verbal fluency, knowledge) functions of declarative memory (Lövdén, Bergman, et al., 2005). Declines in MMSE, visual recognition, verbal fluency, and similarities can mark the prodromal phase of AD up to 9 years prior to diagnosis (Amieva et al., 2005). Behavioral markers for ADRD may even appear very early in the lifespan, including more simplified language use (Snowdon et al., 1996), lower performance on tests of mental ability (Whalley et al., 2000), and poorer grades in school (Dekhtyar et al., 2016). It is completely ambiguous as to whether these behavioral markers reflect early manifestations of ADRD-related disease processes or, alternatively, mental habits and dispositions of self-regulation that persist through the lifespan.

Third-Variable Accounts. Innumerable early-life experiences (including, but not exclusively, those derived from high SES and education) could engender both lifelong habits of activity engagement and social integration, and cognitive health—without any direct effect of engagement on cognition. This is the sort of account that covariate analysis is used to dismiss, but there may be important influences aside from education and SES (e.g., sensitive parenting; the availability of certain sociocultural resources, such as sports teams and other extracurricular activities) that may also impact both strategies of activity regulation and cognition.

Another important candidate for a third-variable account is health, such that cognitive fluency, managing an active lifestyle, and maintaining social ties are all by-products of being healthy (cf. Wettstein et al., 2019). The control of health often does not reduce the engagement-cognition relationship (e.g., Hultsch et al., 1999), but it is typically measured as self-report, which may not be sensitive to underlying health conditions. Age-related declines in fluid abilities, then, may be an inevitable consequence of the unfolding of an intrinsic senescence process (Kirkwood, 2011). Senescence, like virtually all biological and psychological processes, are normally distributed (Fries, 1980), so that individual differences in late-life trajectories, then, may plausibly reflect the biological imperative of aging shaped by secondary aging processes. This account would imply that the most promising pathway to cognitive resilience is simply to augment health and physical fitness.

Other candidates for third-variable explanations include personality traits (e.g., openness and conscientiousness; Hill et al., 2020; Lodi-Smith & Roberts, 2012) and motivational constructs (e.g., purpose; Hill & Turiano, 2014), which may independently contribute to both cognitive resilience and engagement. For example, data from the HRS have shown that changes in social well-being positively correlate with changes in conscientiousness, openness, and emotional stability (Hill et al., 2012), all of which have been related to cognition (Luchetti et al., 2016; Soubelet & Salthouse, 2011).

Recap. It is completely plausible that activity engagement and social integration do have direct effects on cognition, even if also influenced by health, personality, and/or early-life experiences. We also have to consider the possibility that health, personality, and motivation are shaped by engagement (Jackson et al., 2012; Varma et al., 2016), thereby contributing to the causal pathways of the beneficial effects of engagement on cognition. This is the focus of the next section.

Theoretical Accounts: Plausible Causal Mechanisms

The appeal to guide any scientific endeavor with theory is passé, and yet conceptual frameworks in this arena rarely get past the aphorism to "use it or lose it." Progress will require the articulation of theories of specific mechanisms through which daily activities, work, and social interactions can impact cognition. The pathways of these mechanisms are likely multifaceted and complex.

Neurocognitive Pathways

Neurocognitive mechanisms proposed to account for an effect of an engaged lifestyle on cognition include transfer, in which the outcomes of experience on behavior and underlying neural substrates are closely tied to the experience itself, and more generalized mechanisms (e.g., exposure to novelty, effort, reserve).

Transfer. The simplest mechanism that has been used to explain cognitive enhancement from engagement is transfer (Dahlin et al., 2008; Thorndike, 1906). In this view, it is assumed that intellect can be decomposed into a set of discrete elements that are independently enhanced through exercise. "Near transfer" characterizes growth in skills very similar to those exercised (e.g., vocabulary learning improves comprehension of simple sentences), and "far transfer" characterizes growth in skills much beyond those originally exercised (e.g., vocabulary learning improves comprehension in reading a novel). The notion of transfer is more descriptive than explanatory, but there is general agreement that the effects of training are highly specific to the skills that are trained (Simons et al., 2016).

By this account, an active and socially integrated lifestyle would be expected to broadly improve the intellect only insofar as there is consistent exercise of innumerable individual abilities within the implicit task demands of everyday activities (Hertzog, 2009). For example, an active lifestyle might exercise cognition through engagement with ill-defined problems to exercise mental flexibility (Schooler & Mulatu, 2001; Schooler et al., 1999, 2004) or through the task demands of managing multiple activities to exercise executive control (Carlson et al., 2012). Similarly, social interactions and managing social networks make demands on cognition. There is the dance of social interactions: People are complex stimuli that require complex responses at a proper tempo. Social interactions typically require conversation, which exercises language, which in turn depends on working memory (Ryskin et al., 2015), executive control networks (Fedorenko & Thompson-Schill, 2014), and hippocampally mediated declarative memory (Duff & Brown-Schmidt, 2012). Further, social networks have to be managed, which requires memory, planning, and often activity engagement (Brown et al., 2016).

The empirical challenge to testing this idea is to measure the exercised components of engagement relative to psychometrically measured abilities. To the extent that this has been attempted, the mapping of engagement to training gains is not straightforward (e.g., Stine-Morrow et al., 2014; Baniqued et al., 2014). The context in which components are exercised may be critically important (Barnett & Ceci, 2002). There is some evidence from the laboratory that complex skills are better learned and show transfer when they are practiced as a whole rather than as components, especially when task demands require one to frequently shift the priority among the components (Kramer et al., 1995; cf. Brown et al., 2014). In the ecology of human cognition, human behavior is incredibly generative. With a high degree of variability, individuals do things they have never done before on a daily basis. Schooling is predicated on the assumption that students learn some subset of skills that are needed for them to thrive, which will then prepare them to encounter novel challenges for years to come, thereby expanding their repertoires. Thus, the idea that far transfer does not exist (Sala & Gobet, 2017), at least, "in the wild," can be dismissed out of hand. As we return to at the end of the chapter, the principles of how transfer emerges in cognitive ecologies of everyday life remain to be discovered.

Generalized Mechanisms. While transfer-related mechanisms would be expected to produce very specific effects of lifestyle engagement on behavior, more generalized mechanisms have also been proposed to stimulate cognitive growth through engagement. As touched on earlier, exposure to novelty (Hultsch et al., 1999; Staudinger et al., 2020) is suggested to benefit cognition through mental stimulation and changing task demands. Plausibly, novelty may potentiate plasticity, neurochemically through dopaminergic and norepinephrine systems, and psychologically through motivational processes (Düzel et al., 2010; Hidi, 2016; Lisman et al., 2011). Effort (Park et al., 2014; Shors, 2014), in which activities tax existing resources, has also been suggested as a mechanism to support cognitive health. In fact, research with animal models (Shors, 2014) demonstrates that complex activities with complex demands protect again cell death in the hippocampus. Interestingly, cognitive training with a working memory updating task, presumably evoking effort, has been shown to increase the release of dopamine in selected brain regions (Bäckman et al., 2017). Yet another generalized mechanism that has been evoked to account for experience-related cognitive resilience is "reserve" (Stern, 2009), a construct characterizing a mismatch between the observed AD-related neuropathology and behavioral markers (i.e., intact cognition in the presence of neuropathology). The effects of AD-related neuropathology have been found to be buffered by a number of factors, including education, IQ, occupational complexity, and social integration. Stern has distinguished between *brain reserve* ("hardware"), reflecting structural properties of the brain that support function in the presence of neuropathology (e.g., as measured by the volume of gray matter or cortical thickness); and *cognitive reserve* ("software"), which allows one to make better use of neural resources. Much current work is focused on understanding how cognitive reserve is implemented in neural function (Stern, 2017).

Motivational Pathways

Activity engagement and social integration may act on cognition through motivational pathways—in conjunction or not with neurocognitive mechanisms (i.e., engagement → motivation → cognition). In this causal chain, engagement may stimulate motivational resources that act directly to enhance cognitive performance. Further, any neurocognitive pathway is likely to depend on sustained engagement (i.e., motivation → engagement → cognition). Thus, motivational pathways to cognitive health cannot be ignored. We consider motivational resources broadly, so as to encompass dispositional and contextual factors (e.g., self-efficacy, enjoyment, confidence, socioemotional systems).

Personality traits can be situated in both of these causal chains, both in stimulating certain sorts of activities and in directly impacting cognition. Investment theory (von Stumm & Ackerman, 2013) argues that intellect arises out of a sustained commitment to activities that offer opportunities for learning, which are reflected in "investment traits," such as openness to experience, need for cognition, and typical intellectual engagement. Personality traits may also reflect patterns of experiential engagement that may be favorable to cognition (e.g., DeYoung et al., 2009, reported a relationship between the intellect facet of openness and neural activation during a demanding task). A cross-sectional relationship between openness and cognition is well replicated (Deary et al., 2010; Parisi et al., 2009; Sharp et al., 2010; Soubelet & Salthouse, 2010), but evidence for a relationship between openness and cognitive trajectories is mixed (e.g., Hultsch et al., 1999; Luchetti et al., 2016; Sharp et al., 2010; Wettstein et al., 2019; Ziegler et al., 2015). Evidence from longitudinal data has shown that openness can engender differential preservation in fluid ability (Ziegler et al., 2015) and verbal fluency (Hogan et al., 2012), but openness has not been consistently found to reduce cognitive declines (Sharp et al., 2010). Also, Soubelet and Salthouse (2010) did not find support for the mediation of openness-intelligence by self-reported activity engagement. Intellect, and intellectual engagement, may also shape personality. Based on data from the Lothian Birth Cohort Study, von Strumm and Deary (2013) found that verbal fluency was a longitudinal predictor of openness. However, counter to investment theory, openness did not predict fluency. Jackson et al. (2012) found that older adults in an adaptive cognitive training program showed increases in openness relative to a waitlist control, which showed no significant change. Collectively, the data are somewhat mixed but point to the possibility of reciprocal causation (Wettstein et al., 2017). To the extent that personality is a driver of cognition (and/or engagement), it may be a targeted pathway for resilience. Increasingly, personality is recognized to be malleable (Roberts, 2006; Roberts & Mroczek, 2008), making this a promising avenue.

Social support has been called "one of the most well-documented psychosocial factors influencing physical health outcomes" (Uchino, 2009, p. 236). Among the mechanisms to which the salutary effects of social support have been attributed are those related to motivation. For example, attachment security has been argued to engender perceived control and self-efficacy (Uchino, 2009). Similarly, encouragement from close others can stimulate self-care and adherence to health and medical regimens (Robles et al., 2014). Also, social integration may engender habits and dispositions that support health. For example, conscientiousness has been found to be a predictor of social support over time, suggesting that we may cultivate conscientiousness to maintain social support (Hill et al., 2014). The cultivation of conscientiousness may, in turn, foster cognitive health (Luchetti et al., 2016). In fact, conscientiousness is a well-replicated predictor of health and longevity (Deary et al., 2010; Roberts et al., 2008) and has been shown to predict increases in social engagement (but also to be fostered by it; Hill et al., 2014; Lodi-Smith & Roberts, 2012). Thus, social integration may engender a disposition that is favorable for good health and cognition.

On the other hand, motivational factors may sustain engagement (which acts solely via cognitive pathways). For example, one's social network may help to motivate activity engagement even when alone (e.g., one might practice chess strategies to prepare for a game or read a book recommended by a friend). Social networks may motivate cognitive engagement through teamwork and competition (Stine-Morrow et al., 2014) and/or provide social support in persevering through challenges encountered in work, leisure, or navigating everyday problems. Older adults have been found to increase their physical activity more than younger adults when the activity accrued points that were converted to charity donations (Raposo et al., 2020), suggesting that socioemotional context may be particularly important in motivating engagement with aging.

Yet another candidate for motivational effects on engagement is purpose. A sense of purpose has been found to be related to activity engagement (cf. Lewis et al., 2017). Recently, data from the Midlife in the Unitied States (MIDUS) sample have shown that having a sense of purpose is predictive of mortality (Hill & Turiano, 2014), and in cross-sectional data it is related to cognition (Lewis et al., 2017). Thus, it is possible that having a sense of purpose stimulates an engaged lifestyle, which supports cognitive health (though the possibility that activity engagement and social integration are simply manifestations of a purposeful life cannot be ruled out).

The experience of the activity itself may play a role in continued engagement. Flow (Csikszentmihalyi et al., 2005) can occur when an individual engages in an activity that provides a challenge that is well matched to the individual's skill level. An individual in the Flow state is completely immersed in the activity, which is a positive experience argued to have evolved to support the allocation of effort necessary to achieve mastery. Older adults with higher fluid ability have been shown to be more likely to experience Flow during cognitive activities relative to those with lower fluid ability (Payne et al., 2011), implying that ability level may self-perpetuate through selection of activities that one finds enjoyable. Social purpose may differentially influence motivation for activities over the lifespan. The Flow experience has been found to be differentially enhanced with aging when activities have a social purpose (Worm & Stine-Morrow, 2021).

Activity engagement and/or social integration may affect cognitive health through emotional pathways in enhancing well-being and buffering stress (Ryff et al., 2016). So, engagement may indirectly support cognition through health and/or by engendering mental states that are favorable for cognition. Pressman et al. (2009) found that, controlling for age, education, and SES, individuals who spend more time engaged in leisure activities that they enjoy have lower blood pressure, cortisol levels, and body mass indices; better sleep quality; and more positive affect—factors that support cognitive health.

Neuroendocrine Pathways

We have already seen some examples of the neuroendocrine pathways through which activity engagement may benefit cognition (Bäckman et al., 2017; Düzel et al., 2010; Erickson et al., 2011; Hidi, 2016; Lisman et al., 2011). The effects of social integration on neuroendocrine function is perhaps even better documented. As mentioned earlier, both human and animal research shows social isolation is a stressor that increases activity in the hypothalamic pituitary axis, for example, as measured by increases in glucocorticoids (Cacioppo et al., 2015). Glucocorticoids are small molecules that circulate throughout the body, impacting virtually all physiological systems by regulating gene expression. Work with animal models shows that social isolation can lead to glucocorticoid resistance, in which the receptors become less sensitive, so that there is increased release of glucocorticoids and increased inflammatory response, thereby affecting health. Stress also seems to suppress the production of brain-derived natriuretic factor (BDNF), which is necessary for neurogenesis. Based on data from the Framingham Study, Salinas et al. (2017) reported that the relationship between perceived emotional support and dementia risk was mediated by BDNF levels.

Recap

Thus, the causal pathways through which activity engagement and social integration plausibly impact late-life health are likely varied and interacting. In the next section, we consider a framework for developing principles of lifespan cognitive health.

Discovery and Validation of Ecologies for Lifespan Cognitive Health

Any broad effect on cognition from activity engagement and social integration may depend on synergies in the way abilities are exercised in the ecology of lifespan cognition. In fact, recent years have seen a resurgence of interest in ecological approaches (Bronfenbrenner, 1977) to human development and cognition. Individuals are in environments that afford certain opportunities, and within those constraints, they actively construct their lives in selecting what they do and with whom they interact. Recent models in both cognitive optimization (Moreau & Conway, 2014; Stine-Morrow, 2015; Stine-Morrow et al., 2014; van der Maas et al., 2006) and the effects of social relationships on health (Holt-Lunstad, 2018) call for a deeper understanding of the principles governing agentic behavior given ecological opportunities and constraints.

According to this view, in the ecology of everyday life, critical components of cognition are exercised in the context of activities that incorporate "complexity, novelty, and diversity" (Moreau & Conway, 2014, p. 334), such that cognitive skills are exercised together or in close temporal proximity, allowing for their mutual impact (van der Maas et al., 2006). Such a view challenges a long-held assumption in psychology that the positive manifold of abilities that define "intelligence" is reflective of a latent construct. Rather, the positive manifold may emerge dynamically from the exercise of intellectual function within the cognitive ecology (Kovacs & Conway, 2016; Protzko, 2016).

This view is also consistent with neural models of cognition and intelligence as arising out of the flexibility and dynamics of finely tuned and highly interactive components (Barbey, 2018). *Flexibility* is made possible by the brain's remarkable capacity to reconfigure itself—to continually update on the basis of new information and to actively generate internal predictions that guide adaptive behavior and decision making (Clark, 2013; Friston, 2010). Plasticity is therefore critical for the emergence of human intelligence (Barbey, 2018). This perspective implies a departure from the classic view that intelligence originates from individual differences in a fixed set of cortical regions or a singular brain network (cf. Haier, 2016; Posner & Barbey, 2019). Rather, intelligence is argued to originate from individual differences in network mechanisms for flexible and efficient information processing.

The brain has evolved for efficiency—to minimize the cost of information processing while maximizing the capacity for growth and adaptation (Barbey et al., 2013; Bullmore & Sporns, 2012; Ramón y Cajal, 1999). Minimization of cost is achieved through the organization of the cortex into anatomically localized modules, composed of densely interconnected regions or nodes. The spatial proximity of nodes within each module reduces the average length of axonal projections (conserving space and material), increasing the signal transmission speed (conserving time) and promoting local efficiency. This compartmentalization of function enhances robustness to brain injury by limiting the likelihood of global system failure. Indeed, the capacity of each module to function and modify its operations without adversely affecting other modules enables cognitive flexibility and therefore confers an important adaptive advantage. Critically, however, the deployment of modules for coordinated system-wide function requires a network architecture that also enables global information processing. Local efficiency is therefore complemented by global efficiency, which reflects the capacity to integrate information across the network as a whole and represents the efficiency of the system for information transfer between any two nodes. This complementary aim, however, creates a need for long-distance connections that incur a high wiring cost. Thus, an efficient design is achieved by balancing competing constraints on brain organization, demanding a decrease in the wiring cost for local specialization and an opposing need to increase the connection distance to facilitate global, system-wide function.

The human brain balances these competing constraints, creating a small-world topology (Bassett & Bullmore, 2017) in which (a) short-distance connections reduce the wiring cost (high local clustering) and (b) long-distance connections provide direct topological links or shortcuts that promote global information processing. Together, these features enable high local and global efficiency at relatively low cost, providing a parsimonious architecture for human brain organization (e.g., Sporns et al., 2000; van der Maas et al., 2006). Emerging evidence further indicates that general intelligence is directly linked to characteristics of a small-world topology, demonstrating that individual differences in *g* are associated with network measures of global efficiency (Barbey, 2018). These findings motivate further research to elucidate how brain network efficiency changes across the lifespan and contributes to cognitive reserve and resilience in late life.

In measuring the effects of cognitive interventions on static neuropsychological measures without investigating the dynamics and efficiency of brain networks and behavioral plasticity, the idea that experience-related growth in one domain may accelerate learning of a related skill has been largely neglected. Thus, to the extent that mutualism is a core mechanism through which training-specific effects "spread" to produce the positive manifold, there is a significant gap in the cognitive intervention literature that has measured the success of training by transfer to a single instance of performance on a related task—rather than providing the opportunity to *learn* the closely related task.

Math modeling has demonstrated the plausibility of the proposal that the positive manifold can emerge out of a dynamic network in which components reciprocally affect one another (Savi et al., 2019; van der Maas et al., 2006, 2017). This is consistent with behavioral work suggesting that explicit training in flexibly managing multiple tasks can produce transfer (Bjork et al., 2013; Kramer et al., 1995; Shea & Morgan, 1978) and with recent work showing "learning to learn" effects in perceptual training (Kattner et al., 2017), memory (Gross et al., 2013), and working memory (Stine-Morrow et al., in preparation). The implication of this view is that we may miss evidence for pathways to cognitive optimization if we only measure the effectiveness of training or engagement on one-shot measures of abilities, rather than on the subsequent *development* of abilities. In other words, it may be that learning in one domain does not "transfer" to another domain but instead enhances the *plasticity* of a related domain. Activity engagement and social integration, then, may have a causal effect on cognition over time not through the exercise of individual components but by virtue of the way the exercise of components is structured in typical activities.

Another implication of this view is that we need a better understanding of how individuals self-regulate in cognitive ecologies so as to enable exposure to potentially self-enhancing activities over time. According to the corresponsiveness principle (Caspi et al., 2005; Roberts et al., 2008; Scarr & McCartney, 1983), individuals are selected into environments according to existing abilities and traits, which are thereby reinforced by those environments; see also the discussion of transactional models by Lövdén et al. (2020). Applied to intellectual development, this principle suggests that even though people are often selected into environments according to ability, these differences in ability become magnified as a consequence of differentiated engagement (e.g., consider the selection process into university and its lifelong consequences, or the development of domain expertise). There are clearly strong selection pressures for entry into both education and work settings, which thereby shape cognitive trajectories (Deary & Johnson, 2011; Ritchie et al., 2013; Rohwedder & Willis, 2010). It has long been recognized that the development of sociocultural structures to support activity engagement in later life have lagged behind the lengthening lifespans (Riley & Riley, 2000). Enriched environments (Hertzog et al., 2008) afford the opportunity to select experiences that are within the scope of current capabilities and yet create environmental pressures to expand the repertoire of skills (Lawton, 1982; Stine-Morrow, 2015). Small cognitive gains, then, might lead individuals to select into incrementally more complex environments, which would thereby amplify those gains. In one cognitive intervention (Stine-Morrow et al., 2014), older adults who voluntarily continued with the program showed larger cognitive gains in the initial intervention than those who did not. Thus, conceptualizing self-regulation is part and parcel of an ecological study of enrichment, which will ultimately depend on an understanding of socioemotional, dispositional, and motivational mechanisms.

A science of cognitive ecologies that are favorable for development so as to suggest general principles for application will require innovative thinking in approach.

Innovation in Measurement

Technology in recent years has developed to a point of affording the incidental recording of behavior and physiological markers on a large scale. Wearable technology allows easy recording of activity almost as it occurs along with the simultaneous recording of location and physiological data. For example, technology-based updates of time budget diaries (Moss & Lawton, 1982) and day reconstruction (Kahneman et al., 2004) would be fairly easy to implement. Wearables allow for GPS tracking and accelerometry, which may help to validate measures of activity engagement or serve as a proxy for it (Carlson & Varma, 2015; Yen et al., 2015; York Cornwell & Cagney, 2017).

While there is recognition of a distinction between the objective reality of social interaction (e.g., frequency and duration of social contact) and the subjective experience of relationships (e.g., social support; e.g., Kuiper et al., 2015), often the nature of measurement does not allow us to distinguish among different social mechanisms (cf. Gow et al., 2012, p. 250). Constructs that have been investigated in relationship to cognitive health and/or mortality include quality of social networks (Cohen et al., 1997); social support (Cohen et al., 1985; Cutrona & Russell, 1987; Uchino, 2009); loneliness and social isolation (Cacioppo & Hawkley, 2009; Cacioppo et al., 2015); engagement in social roles (Lodi-Smith & Roberts, 2012); and social well-being (Keyes & Simoes, 2012), itself multidimensional, including social contribution (which is related to purpose).

In a recent review, Holt-Lunstad (2018) outlined a systems approach to understand the influences of social relationships on health. Within this view, social relationships can be conceptualized as a system at multiple levels that act synergistically. Some careful work on measurement that is grounded in theory to distinguish influences at different levels of analysis is needed. Some constructs can only be assessed via self-report (e.g., subjective experience of relationships). Subjective experiences may be dissociable and may not operate in the same way (e.g., feelings of emotional closeness vs. social support [feeling you can rely on someone] vs. social contribution [a sense of purpose]). Objective measures of social engagement may reflect very different mechanisms supporting cognitive health (e.g., individual interactions vs. community volunteering)—or not. Systematic examination of this class of potentially powerful protective factors is needed.

Another measurement consideration is what outcomes we should be targeting for improvement. Psychometric intelligence predicts learning and skill development (Beier

& Ackerman, 2005; Burgoyne et al., 2016) and numerous real-world outcomes (Kuncel et al., 2004). However, it is not necessarily the case that engagement with those activities will directly affect intelligence (Sala & Gobet, 2017; Simons et al., 2016). An implication of mutualism is that static measures of *g* may emerge from long-term exercise of cognition in environments in which individuals regulate exposure rather than being a latent causal factor for cognitive success; as such, it may not be an appropriate gold standard for measuring the effects of interventions on cognitive health. Again, technology affords great innovation in assessing cognitive targets in vivo, including using change itself as an outcome. Embedded technology affords the opportunity to develop measurements of authentic learning as cognitive targets.

Technology also affords opportunities to obtain measures of possible mediators of effects of engagement on cognition—thereby informing theory with respect to meaningful ways to operationalize dimensions. For example, the measurements of heart rate and blood pressure (e.g., Hess, 2014; Hess & Ennis, 2011) and pupillometry (e.g., Ayasse & Wingfield, 2020; Piquado et al., 2010; Granholm et al., 2017) have shown promise as ways to operationalize effort. Wide use of smart technology may soon afford inexpensive ways for ecological assessment of this construct. Wearables are currently being used for ecological momentary assessments (EMAs) of stress and affect (Smyth et al., 2018). Retrospective self-reports have been in wide use for some time and will likely continue to have an advantage in terms of cost. Technology-based assessments of concurrent activity engagement could be used to assess the validity of these instruments.

Innovation in Research Designs

Heretofore, the best research designs available to examine how cognition is shaped by engagement have been longitudinal designs in which measurement intervals are on the order of years (Hertzog & Nesselroade, 2003). More intensive measurement, including burst designs, which may capture critical life events expected to impact activity and social engagement (e.g., relocation, death of spouse), might be leveraged as "natural experiments" to probe the effects of lifestyle patterns on cognition (Hofer & Sliwinski, 2006).

The growing recognition of ADRD as a lifespan process of interacting biobehavioral and social systems (Livingston et al., 2017) calls for serious investment in interdisciplinary longitudinal research. Knowledge of the causal chain of early life experiences to lifespan health is thin and largely focused on the effects of extreme poverty, rarely charting effects beyond young adulthood (e.g., Evans & Kim, 2013; Kim et al., 2013). While "developmental continuity" is taken as a given in most introductory textbooks, the empirical work needed to understand connections across the lifespan is difficult to do and expensive. There is growing attention to its importance (Black et al., 2017; McEwen & McEwen, 2017). We learned so much from the Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) trial (Ball et al., 2002; Rebok et al., 2014; Willis et al., 2006), in part because it grew out of a National Institute of Aging funding mechanism that engendered substantive and sustained interaction among individuals with divergent perspectives. The time is ripe for a large-scale study comparable to the

ACTIVE trial to test mechanistic explanations of how engagement may impact cognition (Onken et al., 2014).

There is a critical need for methodological advances that allow us to understand how different sorts of individuals make choices and the consequences for those choices in different ecologies. We need to develop techniques to examine the dynamics through which people select into environments and are changed by them. The treatment of education and other early-life advantages as "nuisance variables" to be controlled does not serve the science well. We need to probe how such experiences shape activity preferences and use experimental designs to (gently) disrupt corresponsiveness.

Intervention research is expensive. Experience-dependent plasticity is often assessed with interventions on the order of 10 to 12 weeks (Ball et al., 2002; Draganski et al., 2004), but neural changes in response to experience have been detected in as little as 7 days (May, 2011). A well-designed training program can produce performance gains and transfer within 3 weeks in an older adult sample, with training gains reaching asymptote within 2 weeks (Payne & Stine-Morrow, 2017). We should consider the use of such "microinterventions" that create conditions for intensive theory-driven intensive lifestyle changes on the order 1 to 3 weeks to evaluate the efficacy of the targeted mechanism for "moving the needle," and then proceeding to longer time periods to be able to evaluate dose-response relationships and issues of adherence.

A key facet of interventions is adherence, which is essential to sustaining effective "doses" of physical and cognitive engagement for cognitive health over long periods of time. Adherence and sustained engagement are more likely for activities that are perceived as personally relevant and vary over time. Interactive technology is increasingly used to promote adherence to such activities. For example, conversational agents (CAs) have been used as virtual companions that engage older adults in social interaction, games, and support adherence to exercise and other activities. CAs have the potential to support older adults' adherence to a variety of intellectually and socially engaging activities at home. Older adults are more likely to continue engaging with CAs that initiate conversations (rather than acting simply as respondents) and share information (e.g., stories) that varies over time (Ring et al., 2015; Sidner et al., 2018).

Innovation in Analytic Approaches

Inevitably, most of the data relevant to the question of causal connections between engagement and cognition will be correlational. There is a long history of heated debate about the use of such data to develop causal accounts to inform public health policy (Grimes & Schulz, 2012; Parascandola et al., 2006; Sheehan et al., 2008). Innovation in methodology will require comparable development of analytic approaches.

Assuming a life course ecological view in which early experiences shape opportunities that may manifest to varying degrees, we should reconsider the implications of statistical control of significant early influences such as education (and related markers such as IQ and academic performance), which may be excessively conservative (Deary & Johnson, 2010). Minimally, such variables might be treated as moderators, which could provide a view into the relative variability and effects of engagement on cognitive outcomes (e.g., McArdle & Prindle, 2008).

Sequence analysis, a technique common in sociology to quantify successive probability structures across the life course (Aisenbrey & Fasang, 2010, Struffolino et al., 2016), has promise. Such techniques might provide a window into the causal chain by illuminating how early-life experiences shape opportunities and/or dispositions to engender engagement—and how cognitive health emerges as a function *of different pathways*. In conjunction with genetic analysis, this could be a powerful tool (Larsson et al., 2017).

Finally, solving this problem will inevitably require large data sets. We have to find ways to balance Type I error against our need for discovery of novel pathways to late-life cognitive health. Clear theoretical motivation, especially an ability to discriminate between competing hypotheses, is a great advantage. Grounded in design considerations, we might routinely include control outcomes that we would NOT expect to be impacted by engagement, much along the research strategy long adopted in the expertise literature (Clancy & Hoyer, 1994).

Conclusions

Old age is yet young, and the sociocultural affordances to maintain health spans (Crimmins, 2015) that are on par with increasing lifespans have yet to be determined (Baltes, 1997). The incomplete understanding of pathways to lifelong cognitive health is among the most pressing scientific problems of our time. Evidence for effects of engaged lifestyles in nurturing cognitive resilience is tantalizing, but "use it or lose it" is an aphorism, not a scientific theory with the specificity to guide policy or enable individuals to make decisions about how to organize their days. The discovery and validation of principles of healthy ecologies will require innovation in measurement, research design, and analytic approaches.

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