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Running Head: CHANGES IN ACTIVITY AND COGNITION

Longitudinal Associations Between Activity and Cognition Vary by Age, Activity Type, and
Cognitive Domain

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Abstract

The demonstration of correlated change is critical to understanding the relationship between activity engagement and cognitive functioning in older adulthood. Changes in activity have been shown to be related to changes in cognition, but little attention has been devoted to how this relationship may vary between specific activity types, cognitive domains, and age groups. Participants initially aged 65 to 98 years ($M=77.46$) from the Australian Longitudinal Study of Ageing ($n=1321$) completed measurements of activity (cognitive, group social, one-on-one social, and physical) and cognition (perceptual speed, immediate and delayed episodic memory) at baseline, two, eight, eleven, and fifteen years later. Bivariate latent growth curve models covarying for education, sex, and baseline age and medical conditions revealed multiple positive level relations between activity and cognitive performance, but activity level was not related to later cognitive change. Change in perceptual speed over 15 years was positively associated with change in cognitive activity, and change in immediate episodic memory was positively associated with change in one-on-one social activity. Old-old adults showed a stronger change-change covariance for mentally-stimulating activity in relation to perceptual speed than did young-old adults. The differentiation by activity type, cognitive domain, and age contributes to the growing evidence that there is variation in the way cognitive ability at different ages is related to activity.

Keywords: Cognition, Activity, Change, Covariation, Young-old, Old-old

Word count: 5095

Comprehensive reviews have concluded that social, physical, and cognitive activity engagement are indeed one possible way to modify cognitive ability as we age (Hertzog, Kramer, Wilson, & Lindenberger, 2009). Research interest is consequently moving beyond basic demonstrations of the association, and instead is now oriented towards identifying the conditions under which activity engagement prevents age-related cognitive decline, and factors that influence the association between activity and cognitive change (Bielak, 2010; Gow, Bielak, & Gerstorf, 2012).

Longitudinal analyses are consequently garnering greater attention. It has been found that more active individuals tend to show less cognitive change (i.e., decline) over time (e.g., Sturman et al., 2005; H. X. Wang et al., 2013; Wilson et al., 2002), and are less likely to develop dementia (Karp et al., 2006; Wilson et al., 2002), or delay its onset (Hall et al., 2009). However, the association of baseline activity level predicting cognitive change is not in any way a guarantee of causality, and it is important to distinguish whether the analysis was entirely focused at the group level, as the previous studies were, or based on individualized change. For example, a series of papers found few relationships between baseline social, cognitive, and physical activity with various domains of within-person cognitive change (i.e., fluctuation from an individual's own mean activity score) (Brown et al., 2012; Lindwall et al., 2012; Mitchell et al., 2012).

Further, the association between change in activity and change in cognition has been less studied, but is perhaps the more significant. If two variables are believed to be dynamically linked in some way, the variation over time in both variables must be associated. For example, for concurrent links, an increase in activity participation over 10 years would be associated with an increase (or less decline) in cognitive functioning over the same period. Alternatively, there

may be a time lag of weeks, months, or years between change in one variable and change in the other. The few investigations conducted thus far are promising, and positive change-change relationships have been found across a variety of samples (Ghisletta, Bickel, & Lövdén, 2006; Hultsch, Hertzog, Small, & Dixon, 1999; Lövdén, Ghisletta, & Lindenberger, 2005; Mackinnon, Christensen, Hofer, Korten, & Jorm, 2003; Small, Dixon, McArdle, & Grimm, 2012).

However, variation by activity domain in these dynamic associations is a further consideration. Hertzog et al. (2009) concluded that in studies that compare physical, cognitive, and social activity in relation to cognitive change, cognitive activity tends to be the strongest predictor (Bielak, Hughes, Small, & Dixon, 2007; Ghisletta et al., 2006; Verghese et al., 2006; J. Y. J. Wang et al., 2006; Wilson et al., 2002). Even a robust effect of physical activity on cognitive decline was no longer significant after controlling for cognitive activity (Sturman et al., 2005).

On other hand, being socially active has been associated with less cognitive decline even when cognitive and physical activity were included in analyses (James, Wilson, Barnes, & Bennett, 2011). Further, not all social activities may be equal, as Jopp and Hertzog (2010) found that private social activities were more strongly linked to cognition than public social activities that are typically done in larger groups. Finally, there is also evidence that self-reported physical activities may be the primary predictors of cognitive change (e.g., Gow, Corley, Starr, & Deary, 2012). Using a unique birth cohort sample, the effect of leisure activity (i.e., crafts, reading, cards) on cognitive change was attenuated with the inclusion of cognitive scores from age 50, but physical activity remained a significant predictor of 30 year cognitive change (assessed at ages 60, 70, and 80) (Gow, Mortensen, & Avlund, 2012). Further variations have been found for studies specifically investigating dynamic effects, where cognitive activity has been found to

have the strongest coupling relationship with cognition (Mitchell et al., 2012), but the link does also exist for both the physical and social domains (Small et al., 2012). Consequently, the activity engagement type that shows the closest association with cognitive change is still debatable.

Further complicating our understanding of this relation is the range of cognitive domains investigated in the literature. Depending on the study, different activity types are associated with different cognitive domains, and there is no consistent pattern amongst the associations (Bielak, 2010). It has been suggested that perceptual speed may be particularly sensitive to associations with activity level given the notable declines associated with normal aging, and there is evidence to support this hypothesis with social, leisure, and media activities (Ghisletta et al., 2006; Lövdén et al., 2005). In contrast, a meta-analysis concluded that physical exercise was particularly associated with not only processing speed, but also executive functioning and effortful, visuospatial tasks (Colcombe & Kramer, 2003). Although it is not possible for all studies to evaluate each cognitive domain, assessment of multiple cognitive abilities in any one study is recommended so as to provide a more thorough examination of the associations with activity (Gow, Bielak, et al., 2012). Consequently, the present study included an index of perceptual speed and two memory tasks in the analyses.

Finally, age is typically overlooked as a possible moderator in the relationship between lifestyle engagement and cognitive ability, and tends to only be included as a covariate. Although the variety and frequency of activity participation can be relatively similar across older adulthood (Parisi, 2010), those in younger old age tend to participate in more challenging activities than those in the later older years (Paillard-Borg, Wang, Winblad, & Fratiglioni, 2009). In fact, the oldest old (85+ years) are more likely to preoccupy themselves with passive activities

such as watching television or listening to the radio (Paillard-Borg et al., 2009). Moreover, because of the disparate scores on cognitive tasks within older adulthood (Salthouse, 2004), and the likelihood for greater age-related heterogeneity compared to younger adult groups, it is reasonable to expect that the strength of the link between activity participation and cognitive ability is moderated by age. Specifically, activity and cognition have been found to be more strongly linked amongst older compared to younger or middle-aged adults (Hillman et al., 2006; Parslow, Jorm, Christensen, & Mackinnon, 2006), but not all research supports this finding (Bielak, Anstey, Christensen, & Windsor, 2012; Salthouse, Berish, & Miles, 2002).

It is also possible that differential age effects may not be apparent until later older adulthood. The few studies that have specifically contrasted older age groups have shown that cognitive ability in adults aged 75 years and older is more closely associated with activity than is that amongst adults aged 55-64 years, and 65-74 years both in terms of level-level (Hultsch, Hammer, & Small, 1993) and change-change relations (Bielak et al., 2007). Possible age differences in older adulthood may be due to the hypothetical construct of cognitive reserve, also described as the accumulation of compensatory reserves derived from factors (e.g., activity engagement, education) that allow an individual to maintain normal cognitive functioning despite neurological insult or disease (Park & Reuter-Lorenz, 2009; Stern, 2002). Given their reduced cognitive ability compared to young-old adults, old-old adults may require additional support in the form of the environmental aspects of reserve, and draw greater benefit from frequent lifestyle engagement.

The present study evaluated possible variations as a result of activity type, cognitive domain, and age group in the relationship between activity engagement and cognitive ability in a sample of older adults followed for up to 15 years. Associations between diverse activity

(cognitive, group social, one-on-one social, and physical) and cognitive (perceptual speed, immediate and delayed episodic memory) domains were first analyzed using bivariate latent growth curve models, with particular attention given to the correlation of change in the two factors. Next, the influence of age group was investigated with multiple group bivariate latent growth curve models, which compared differences between the young-old and the old-old. Due to evidence of possible variations in cognition and activity level on the basis of age, education level, sex, and physical health (Aarts et al., 2011; Munro et al., 2012; Paillard-Borg et al., 2009; Parisi, 2010), these effects were also accounted for in each analysis.

Method

Participants

The study sample was drawn from the Australian Longitudinal Study of Ageing (Luszcz et al., 2007). Potential participants included those aged 70 years or older who lived in either the community or residential care in the metropolitan area of Adelaide, South Australia. Participants were recruited through the electoral roll, for which registration is compulsory for Australian citizens. Of the 2,703 residents eligible for study inclusion, 1,477 (55%) agreed to participate. Spouses of participants who were over 65 years of age and co-residents over 70 years of age were also invited to participate, resulting in a further 610 participants.

At baseline, the 2,087 participants were aged between 65 and 103 ($M = 78.16$, $SD = 6.69$), and approximately half of the sample was female (49.4%). The outcome measures pertinent to the present analyses were collected at Waves 1 (September, 1992–February, 1993), 3 (September, 1994–February, 1995), 6 (September, 2000–February, 2001), 7 (September, 2003–April, 2004), and 9 (November, 2007–June, 2008); that is, at baseline and after approximately two, eight, eleven, and fifteen years. The standard deviation in the testing interval was less than

3 months for each wave. Data were collected in the participant's residence, and measures for the present study were assessed in a personal interview and clinical assessment. The personal interview included a range of self-reported demographic, psychosocial, and health measures. The clinical assessment included objective measures of psychological and physical functioning and was completed approximately 2 weeks later (Luszcz, Bryan, & Kent, 1997). The clinical component included the cognitive measures of interest for the present analyses, while the activities and covariates were self-reported in the home interview.

Participants were excluded from the present analyses if they scored less than 24 on the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) at any time point (Anstey et al., 2010; Folstein, Anthony, Parhad, Duffy, & Gruenberg, 1985). To maintain consistency across analyses, participants were required to have valid data for all covariates, and data for at least one cognitive measure and one activity composite at one time point. This resulted in a final sample of 1,321 participants, with a mean length of follow-up of 2.72 waves ($SD=1.16$) covering an average of 5.81 years ($SD = 4.94$). Specifically, the number of participants completing each wave was as follows: Wave 3, $n=1165$; Wave 6, $n=595$; Wave 7, $n=354$; and Wave 9, $n=127$.

Relative to those excluded from the present analyses, included participants were significantly younger ($t(1, 2085) = -11.533, p<.001; M_{diff} = 3.40$ years) and more likely to have continued their schooling past age 14 ($\chi^2 = 21.65, df=1, p<.001; 47.7\%$ versus 37.2%). Of those not included in the present study, 39% were excluded due to having a MMSE score less than 24 at some point across the 15 years. This is further demonstrated by the difference in baseline MMSE score for those in the present paper ($t(1, 2042) = 23.82, p<.001; M=28.32$) and those who were excluded ($M=24.22$). Relatedly, the participants included in the study spent more days per

week engaged in cognitive ($t(1, 2060) = 10.67, p < .000; M_{diff} = 1.21$) and group social ($t(1, 2043) = 3.78, p < .001; M_{diff} = .14$) activities at baseline than participants who were excluded. A difference in the same direction was also found for frequency of engaging in physical activities every two weeks ($t(1, 2085) = 2.42, p < .05; M_{diff} = .85$). Because of the multiple stages of the baseline assessment, the majority of participants excluded from the present analyses did not complete the Wave 1 cognitive measures, preventing comparison of the groups on these variables. The groups did not differ in number of baseline medical conditions, sex composition, or engagement in one-on-one social activities.

Measures

Activity Participation

We used 6 items from the Adelaide Activities Profile (Clark & Bond, 1995) to assess the frequency of participation in cognitive and social activities. Each item had four response options tailored to each activity. Participants were asked to indicate how often they participated in each activity in a typical 3-month period. In order to combine the response frequencies into activity domains, we transformed the reported frequency for each activity into days per week engaged in the activity (e.g., Verghese et al., 2006). For example, participating in outdoor social activities once a month was converted to .25 days/week; once every 2 weeks was converted to .50 days/week; and once a week or more was converted to 1 day/week. The six items were divided into three overarching activity categories based on theoretical similarity: 1) Group social: social activities at a club or centre, and outdoor social activities; 2) One-on-one social: initiating telephone calls to friends or family, and inviting others to their home; and 3) Cognitive: reading, and spending time doing a hobby that involves some active participation and thought (e.g., knitting, crosswords, painting). The differentiation amongst the social activities into one-on-one

and group categories was further supported by a factor analysis by Jopp and Hertzog (2010). Participation frequency for both items in each activity category was summed to create total hours per week engaged in each category. Activity totals were then converted to T-scores centered at baseline.

Physical activity was assessed via two questions. Participants were asked to report the number of sessions they walked in the past two weeks, and the number of sessions they engaged in vigorous exercise (i.e., that made them breathe harder or puff or pant) in the past two weeks. Using metabolic equivalent values (MET; mL of used oxygen/minute) for light and vigorous activities for guidance (Physical activity guidelines advisory committee, 2008), a single physical activity score was calculated by $(1 \times \text{walking sessions}) + (3 \times \text{vigorous sessions})$.

Cognitive Ability

Perceptual speed was measured by the Digit Symbol Substitution test (Wechsler, 1981). Participants were presented with a coding key pairing numbers 1-9 with nine symbols. Participants were given 90 seconds to transcribe as many symbols as possible that corresponded to the randomly-ordered presented numbers. The score was the number of items correctly coded.

Immediate and delayed episodic memory were measured by the 15-item Boston Naming Test (Mack, Freed, Williams, & Henderson, 1992). Participants were shown a series of 15 pictures and asked to name the object pictured. Following the naming task, participants were asked to recall the names of as many pictures as they could, and this represented their immediate episodic memory score. Participants then completed two other cognitive tasks lasting approximately 10 minutes. They were again asked to recall the names of as many pictures as possible, and this represented their delayed episodic memory score.

Covariates

We chose to control for the effects of sex, education, baseline number of medical conditions, and baseline age. Approximately half of the participants were female (48.1%). *Education* was assessed by a binary measure of the age participants left formal schooling: before age 15 ($n = 690$), or at age 15 or older ($n = 631$). *Medical conditions* were based on the number of self-reported current chronic conditions from a comprehensive list of 37 diseases (e.g., arthritis, heart disease, cancer; $M = 2.52$; $SD = 1.67$; 0-10). *Baseline age* was calculated to the nearest day ($M age = 77.46$, $SD = 6.11$), and this variable was also used to create a binary age group variable for use in the multiple group analyses. Participants were divided into those up to 76 years of age ($n = 596$; $M age = 72.04$, $SD = 2.54$; 65-75.99 years) and those 76 years and older ($n = 725$; $M age = 81.92$; $SD = 4.31$; 76-97.71 years). This age division was necessary to obtain similar *ns* between the groups, while also permitting model convergence.

On average, at baseline participants engaged in cognitive activity for 5.38 hrs/week ($SD=2.40$), group social activity for 0.8 hrs/week ($SD=.81$), one-one-one social activity for 3.82 hrs/week ($SD=2.16$), and physical activity for 5.11 sessions every 2 weeks.

Data Preparation & Statistical Analysis

To aid in comparison across measures, all activity summary scores and cognitive scores were converted to a standardized T metric ($M = 50$, $SD = 10$), using the mean scores of the baseline sample as the reference ($n = 2,087$). To examine activity–cognition interrelations in change, we used a bivariate latent growth curve model (LGM; (McArdle, 1988); see also (Hoppmann, Gerstorf, Willis, & Schaie, 2011). As a straightforward extension of a univariate LGM, a bivariate LGM estimates fixed effects (average levels and slopes) and random effects (inter-individual differences in levels and slopes). Intercepts and slopes are estimated at the population level and are allowed to vary and co-vary. The fixed quadratic effect was also

estimated. The time-specific residuals are assumed to have a mean of zero and exhibit occasion-invariant variances. In total, the model estimated 63 free parameters. Models were estimated based on all data points available using the full information maximum likelihood estimation algorithm, which allowed accommodating incomplete data under the missing at random assumption (Little & Rubin, 1987). We used the *Mplus* program version 6 (Muthén & Muthén, 1998-2011).

Three sets of models were tested. In a first step, we conducted univariate LGMs to assess change in the activity and cognitive measures. Next, we estimated bivariate growth models for each activity category and cognitive ability combination and determined if inter-individual differences in level and change existed. To examine whether variation existed by age group, cognitive domain, or activity type, our primary focus was on whether and how individual differences in change in activity participation were associated with individual differences in change in cognitive performance. In a third step, we examined whether the strengths of across-domain associations differed by age group using a statistically thorough, yet straightforward and parsimonious multi-group approach. In this approach, we compared a baseline model where all parameters were freely estimated in the two age groups to models that constrained all variances to be equal across groups, and finally set all covariances invariant. Changes in model fit were analyzed for significance. All analyses controlled for years of education, number of baseline medical conditions, baseline age, and sex.

Results

Table 1 shows the parameters associated with the univariate LGMs, and Figure 1 illustrates the model-implied change for the activity (part a) and cognitive measures (part b). Specifically, only one-to-one social activity increased over time. The rest of the activity

measures did not show significant linear or quadratic change, but significant individual differences were evident. Both episodic memory measures declined over time, but there was no significant change in perceptual speed. However, there was significant variation between individuals over time in perceptual speed. Estimates related to the covariates are presented in Supplementary Table 1.

Associations between Activity and Cognitive Ability

Table 2 provides the model fit statistics and standardized parameter covariance estimates for each bivariate LGM (also see Supplementary Table 2 for models comparing measures of the same domain). The most common relationship was a link between levels of activity and levels of cognitive ability. In each case, this association was positive, indicating that higher activity participation was associated with higher cognitive performance. Participation in group social activity showed the most consistent relationship with each cognitive domain (i.e., $\beta = .254, .228, .210$ for perceptual speed, immediate, and delayed episodic memory, respectively), followed by participation in cognitive activity in relation to perceptual speed ($\beta = .283$) and immediate episodic memory ($\beta = .104$).

Higher immediate memory scores were also associated with less physical activity participation over time, but less change in cognitive activity over the 15 years. Notably, activity level was not related to cognitive change for any combination of bivariate LGM.

The covariance between the slope parameters was significant for only two of the twelve bivariate LGMs. Change in perceptual speed over time was positively associated with change in cognitive activity ($\beta = .540$), and change in immediate episodic memory was positively associated with change in one-to-one social activity ($\beta = .635$). Therefore, participants who showed less decline than others in the sample also tended to show less decline than others on

cognitive activity and vice versa. Similarly, those who declined less than others in episodic memory also tended to be stable or even increase more than others in one-on-one social activity. Additional analyses accounting for the effects of having a spouse in the sample did not change the results.

Differences in Associations between Activity and Cognitive Domain by Age Group

The fixed quadratic effect for the activity and cognitive measures produced model misspecification even when the slopes were constrained, and hence was removed from these models. There was little evidence of significant age group differences across the various combinations of activity domain and cognitive task. For cognitive activity, the only significant difference between the age groups was in relation to perceptual speed. Compared to a model with the variances constrained to be equal across the two groups, a model additionally constraining the covariances resulted in significantly worse model fit to the data ($\Delta\chi^2 = 16.75$, $\Delta df = 6$, $p < .025$). Evaluation of covariance estimates with all parameters free to vary showed that the young-old had fewer significant covariance relationships between cognitive activity and perceptual speed than the old-old group (see Figure 2). The young-old adults only showed a positive significant relationship between cognitive activity level and perceptual speed level, an effect that was much stronger in the old-old. In addition, the old-old group had a significant negative relationship between activity level and cognitive slope, indicating that individuals with higher cognitive activity level also tended to have greater negative change in perceptual speed over time. Further, there was a strong positive association between cognitive activity slope and perceptual speed slope, demonstrating that changes in cognitive activity were associated with changes in perceptual speed.

The two age groups did not significantly differ in their covariance relationships for group-based social activity or one-on-one social activity. There were significant age-related effects for physical activity for all cognitive domains. However, this difference was not due to the covariances between physical activity and cognitive ability, but rather due to variation between the age groups in the level and slope relations for physical activity. In every case, the young-old group showed a stronger association between physical activity level and slope than the old-old group.

Discussion

The purpose of the present study was to examine the longitudinal relationship between various domains of activity engagement and cognitive ability, with particular attention to the covariation of change and differentiation as a result of stage of older adulthood. Generally, there were multiple positive level relationships between activity and cognitive performance, but fewer associations between activity change and change in cognition. Further, there was a variety of patterns of associations across the activity and cognitive domains, with cognitive activity being primarily linked to perceptual speed change, and one-on-one social activity showing a strong change association with immediate episodic memory. There were significant differences between the young-old and old-old in the change-change covariation, but only for mentally-stimulating activity in relation to perceptual speed.

The relative dearth of change relationships between activity participation and cognitive performance compared to level associations is consistent with the literature (e.g., Bielak et al., 2007). Surprisingly however, activity level was not related to later cognitive change. Relatedly, there was only one instance of cognitive level being associated with change in activity, and one nearly significant association that was paradoxically in the direction of a higher cognitive score

being associated with a greater decline in activity participation. The assumption that changes to cognitive ability lead to changes in activity participation is equally as plausible as the more common assumption that activity engagement results in cognitive maintenance. Investigations have found evidence of the plausibility of both pathways (Hultsch et al., 1999), but mixed results regarding the superiority of either pathway (Ghisletta et al., 2006; Lövdén et al., 2005; Small et al., 2012).

There was evidence that change in cognitive performance was related to change in activity across 15 years, but only in two of the 12 possible instances. The scarcity of these effects may have arisen for a number of reasons, including the possibility that only certain activity domains show significant change covariation with certain cognitive domains (Bielak, 2010). Further, there is a distinction between change where the time-varying variable has been partitioned into its' between- and within-person components, and one that uses the entire variable to evaluate change (Hoffman & Stawski, 2009). Studies that have divided the variable accordingly have revealed inconsistent results (Bielak et al., 2012; Brown et al., 2012; Lindwall et al., 2012; Mitchell et al., 2012), and other studies using the overall change approach (as in the present study) have found only specific change relationships (Hultsch et al., 1999). Additional research investigating both methods, and using a wide variety of activity and cognitive domains would be beneficial.

There were significant differences in findings depending on activity domain. Regarding level-level associations, greater participation in social and cognitive activity was associated with greater performance on the perceptual speed and immediate episodic memory tasks, but physical activity showed no associations. Changes in cognitive and physical activity were both related to

immediate memory level, but the two significant slope-slope covariance relationships included cognitive and one-to-one social activity.

Similar patterns of primarily significant social and cognitive activity effects, but not physical activity effects are not unheard of in the literature, but not all follow this trend (e.g., Gow, Mortensen, et al., 2012; James et al., 2011). One-on-one social and cognitive activity, in particular, may have had longitudinal links for the following reasons. Socially engaging with one other person or a few people would presumably involve a different level of cognitive challenge than when engaging in a large group of individuals. The present discrepancy in the social activity results confirms this distinction, as does cross-sectional data where a stronger link with cognition was found with private compared to public social activities (Jopp & Hertzog, 2010). Jopp and Hertzog suggested that social activities with a smaller group of individuals may provide additional emotional support and wellbeing that is missing from larger group activities, spurring its relation to cognition. Cognitive activity participation on the other hand is hypothesized to have a more direct association with the neurological and cognitive systems, “exercising” the brain through activities like crossword puzzles, and impacting synaptic connections, cerebral blood flow, or even neural efficiency (Kramer, Bherer, Colcombe, Dong, & Greenough, 2004; Park & Reuter-Lorenz, 2009; Stern, 2002). Based on the extant literature, cognitive activity has also been declared the strongest predictor of all activity domains (Hertzog et al., 2009). The failure to find significant relationships for physical activity was unexpected, but might reflect the relatively poorer model fit associated with this variable in our analyses. Hence, the findings for physical activity should be interpreted with caution.

The pattern of results differed across the cognitive domains. It appears that perceptual speed was particularly attuned to mentally-based activity, one-on-one social activity was best

characterized by immediate episodic memory, and group social activity held similar level-level associations with all domains. Therefore, despite arguments and demonstrations to the contrary (Ghisletta et al., 2006; Lövdén et al., 2005), perceptual speed may not necessarily be the best choice for analysis in relation to activity engagement. Rather, memory ability also appears to be relevant (Mitchell et al., 2012; Small et al., 2012), and components of memory such as semantic and working memory (Wilson et al., 2002), and delayed and immediate recall (Carlson et al., 2012) have shown divergent results. These discrepancies, together with the present results, demonstrate the value of separating the disparate types of memory, and examining as many diverse cognitive domains as possible.

We found evidence to support the hypothesis that old-old adults show a stronger association between their activity level and cognitive performance than young-old adults: only the old-old group showed a positive slope-slope effect between cognitive activity engagement and processing speed. Because this age differentiation was apparent for only one comparison, the magnitude of age effects was less profound than expected. However, this indicates that there appears to be something unique about how cognitively challenging activity participation and perceptual speed ability change over time for old-old compared to young-old individuals. The link between these domains may exist because perceptual speed is amongst the domains that shows the greatest decline with age (Salthouse, 2004), and cognitive activity is often the strongest predictor over and above other activity types (Hertzog et al., 2009). This combination, together with the possibility of reduced cognitive reserve, may explain why this particular association is stronger amongst the old-old. As no other study has ever directly contrasted the covariation of activity and cognition as a function of older adult age group, replication of this finding is needed.

Our analytic strategy entailed a series of limitations that must be considered. First, bivariate LGMs do not allow inferences about temporal ordering between variables. Second, there is the possibility that the multiple group bivariate LGM is only capable of detecting large differences between groups (Hertzog, Lindenberger, Ghisletta, & von Oertzen, 2006; but also see Rast & Hofer, 2013). Therefore, it is feasible that further relations or age group differences may exist but the present models had limited statistical power to detect them. If this is true however, the two change associations we did find may be the most robust. Third, there was variation in how the cognitive and social activity domains were assessed compared to the physical domain, and the measurement of activity was relatively simple, relying on only 8 items. However, the presence of significant change effects suggests that a more comprehensive activity measurement may not be necessary to find effects with cognition in older age, particularly over a 15-year timeframe. Finally, we note that the skewed distribution in some of our activity measures (group social and physical) would ideally have required adjustments for zero-inflated Poisson distributions. However, implementing these is not a straightforward endeavor and was asking too much of the data at hand. It is thus upon future research to determine whether our findings can be replicated either with less skewed measures or with less sparse longitudinal data that allow estimating bivariate multi-group growth models with zero inflation (see Yao & Liu, 2013).

The present study demonstrates that although change relationships between activity and cognition can exist across a 15-year time period, there is significant variation in these associations depending on whether mental, physical, or private or public social activity is being investigated, and in accordance with which cognitive domain. These associations are further complicated by the stage of older adulthood, where change in cognitive activity is linked to change in processing speed, but only for the old-old. Our results contribute to the mounting

evidence that the relationship between activity engagement and cognitive performance in older adulthood is dependent on a series of moderating factors including the type of engagement, the type of cognitive demand, and the age of the participant. Greater acknowledgement and explicit investigation of these variables is needed.

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Table 1. Estimates from univariate LGMs for each activity and cognitive domain.

	Activity measures				Cognitive measures		
	Cognitive	Group social	1-1 social	Physical	Perceptual speed	Immediate episodic memory	Delayed episodic memory
	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)
Fixed effects							
Level	50.26 (.55)***	50.77 (.59)***	47.08 (.56)***	53.03 (.63)***	51.59 (.53)***	50.89 (.54)***	50.27 (.56)***
Linear slope	-.28 (.23)	+.26 (.28)	+.98 (.24)***	.01 (.26)	-.29 (.20)	-1.08 (.25)***	-1.00 (.24)***
Quadratic slope	.001 (.02)	-.02 (.02)	-.08 (.02)***	-.02 (.02)	-.02 (.02)	.04 (.02)*	.05 (.02)*
Random effects							
Variance: level	42.82 (3.04)***	41.14 (3.52)***	43.73 (3.18)***	54.47 (3.94)***	46.02 (2.76)***	30.01 (2.84)***	37.33 (2.96)***
Variance: linear slope	.19 (.05)***	.14 (.06)*	.13 (.05)**	.19 (.05)**	1.52 (.04)***	.09 (.05)	.08 (.05)
Covariance: level-linear slope	-.93 (.36)*	-.92 (.42)*	-1.18 (.34)**	-2.39 (.40)***	-.71 (.28)*	1.04 (.34)**	.22 (.33)
Residual variance	46.20 (1.66)***	62.91 (2.31)***	45.83 (1.76)***	65.36 (2.23)***	25.32 (1.09)***	44.61 (1.83)***	41.42 (1.69)***
Model fit							
χ^2 (21)	15.27	30.53	42.34	148.76	93.00	27.31	26.96
CFI	1.00	.972	.973	.749	.951	.991	.993
RMSEA	.000	.019	.028	.068	.052	.015	.015

Note. CFI = comparative fit index; RMSEA = root mean square error of approximation. All models covary education, sex, baseline health, and baseline age. Estimates are unstandardized. Each measure was converted to T-score units using the baseline sample (N = 2087). The random effect of the quadratic slope was not estimated.

*p<.05. **p<.01. *** p<.001.

Table 2. Standardized parameter covariance estimates for bivariate LGMs between each activity and cognitive domain.

Cognitive domain	Activity domain	Model fit	Level – Cognition		Linear Slope - Cognition	
			Level – Activity	Linear Slope – activity	Level – Activity	Slope – Activity
Perceptual speed	Cognitive	$\chi^2 = 139.48, p < .001$; CFI = .964; RMSEA = .030	.283***	-.018	-.073	.540**
	Group social	$\chi^2 = 152.16, p < .001$; CFI = .952; RMSEA = .033	.254***	-.078	-.015	.233
	1-1 social	$\chi^2 = 159.93, p < .001$; CFI = .958; RMSEA = .034	.156**	-.214	.070	.253
	Physical	$\chi^2 = 261.27, p < .001$; CFI = .900; RMSEA = .049	0	-.030	.010	.138
Immediate episodic memory	Cognitive	$\chi^2 = 53.84, p > .50$; CFI = 1.00; RMSEA = .000	.104*	.330*	.318	-.155
	Group social	$\chi^2 = 83.21, p < .05$; CFI = .982; RMSEA = .016	.228***	.124	.071	.272
	1-1 social	$\chi^2 = 106.00, p < .001$; CFI = .972; RMSEA = .023	.107 (p=.05)	.044	.070	.635*
	Physical	$\chi^2 = 190.90, p < .001$; CFI = .897; RMSEA = .039	.072	-.262 (p=.051)	.083	.026
Delayed episodic memory	Cognitive	$\chi^2 = 57.36, p > .50$; CFI = 1.00; RMSEA = .000	.090	.224	.083	.008

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Group social	$\chi^2 = 88.63, p < .05$; CFI = .979; RMSEA = .018	.210***	-.020	-.096	.327
1-1 social	$\chi^2 = 97.95, p < .01$; CFI = .979; RMSEA = .020	.100 (p=.05)	.169	-.123	.326
Physical	$\chi^2 = 190.89, p < .001$; CFI = .904; RMSEA = .039	.064	-.201	-.048	.258

Note. CFI = comparative fit index; RMSEA = root mean square error of approximation. All models covary education, sex, baseline health, and baseline age. All models included the quadratic fixed effect.

*p<.05. **p<.01. *** p<.001.

Supplementary Table 1. Covariate estimates from univariate LGMs for each activity and cognitive domain.

	Activity measures				Cognitive measures		
	Cognitive	Group social	1-1 social	Physical	Perceptual speed	Immediate episodic memory	Delayed episodic memory
	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)
Sex							
Level	.70 (.51)	.71 (.55)	6.07 (.52)***	-2.43 (.59)***	.53 (.50)	2.70 (.49)***	3.63 (.51)***
Linear slope	-.09 (.20)	-.12 (.25)	-.28 (.21)	.33 (.23)	.06 (.18)	-.01 (.22)	-.30 (.21)
Quadratic slope	.01 (.02)	.01 (.02)	.01 (.02)	-.02 (.02)	-.001 (.01)	.004 (.02)	.02 (.02)
Education							
Level	2.51 (.50)***	.39 (.54)	1.93 (.51)***	.80 (.59)	3.60 (.49)***	.77 (.48)	.76 (.50)
Linear slope	-.04 (.20)	-.43 (.24)	-.42 (.21)*	-.44 (.23)*	-.17 (.17)	.48 (.22)*	.44 (.21) *
Quadratic slope	.007 (.02)	.04 (.02)*	.04 (.02)*	.03 (.02)	.01 (.01)	-.03 (.02)	-.03 (.02)*
Health							
Level	.06 (.15)	-.25 (.16)	.17 (.16)	-.59 (.17)**	-.48 (.15)**	-.32 (.15)*	-.27 (.15)
Linear slope	-.06 (.06)	-.03 (.08)	-.05 (.07)	.01 (.07)	-.02 (.06)	.11 (.07)	.05 (.07)
Quadratic slope	.005 (.005)	-.001 (.006)	.004 (.005)	.003 (.006)	.002 (.005)	-.01 (.01)	-.003 (.006)
Age							
Level	-.08 (.04)	-.11 (.05)*	-.11 (.04)*	-.11 (.05)*	-.64 (.04)***	-.37 (.04)***	-.36 (.04)***
Linear slope	.01 (.02)	-.02 (.02)	.02 (.02)	-.03 (.02)	-.07 (.02)***	-.07 (.02)**	-.09 (.02)***
Quadratic slope	-.002 (.002)	.001 (.002)	-.004 (.002)*	.002 (.002)	.003 (.002)	.005 (.002)*	.006 (.002)**

Note. Estimates are unstandardized.

*p<.05. **p<.01. *** p<.001.

Supplementary Table 2. Standardized parameter covariance estimates for bivariate LGMs within activity and cognitive domains.

			Level - Variable 1		Linear Slope - Variable 1	
			Level – Variable 2	Linear Slope – Variable 2	Level – Variable 2	Linear Slope – Variable 2
Activity domains						
Variable 1	Variable 2	Model fit				
Cognitive	Group social	$\chi^2 = 63.85, p > .5$; CFI = 1.00; RMSEA = .000	.064	.053	.188	-.155
	1-1 social	$\chi^2 = 88.81, p < .05$; CFI = .984; RMSEA = .016	.155**	-.257*	.037	.251
	Physical	$\chi^2 = 191.46, p < .001$; CFI = .873; RMSEA = .038	.062	-.060	-.011	.289
Group social	1-1 social	$\chi^2 = 106.27, p < .05$; CFI = .966; RMSEA = .025	.246***	-.081	-.054	.456
	Physical	$\chi^2 = 206.01, p < .001$; CFI = .841; RMSEA = .040	.223***	-.253*	-.485***	.767**
1-1 social	Physical	$\chi^2 = 235.91, p < .001$; CFI = .872; RMSEA = .044	.099*	.007	-.046	.133
Cognitive domains						
Variable 1	Variable 2	Model fit				
Perceptual speed	Immediate episodic memory	$\chi^2 = 170.67, p < .05$; CFI = .959; RMSEA = .034	.619***	.232*	.051	.692***
	Delayed episodic memory	$\chi^2 = 194.35, p < .001$; CFI = .952; RMSEA = .036	.530***	-.064	.073	.769***

Note. CFI = comparative fit index; RMSEA = root mean square error of approximation. All models covary education, sex, baseline health, and baseline age. All models include the quadratic fixed effect. Model with two memory types was misspecified.

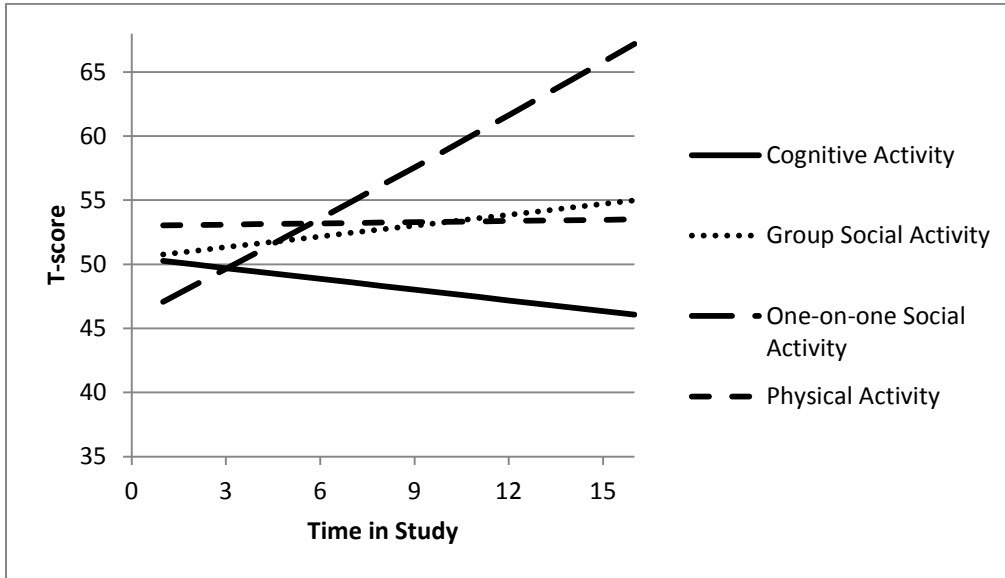
*p<.05. **p<.01. *** p<.001.

Figure Captions

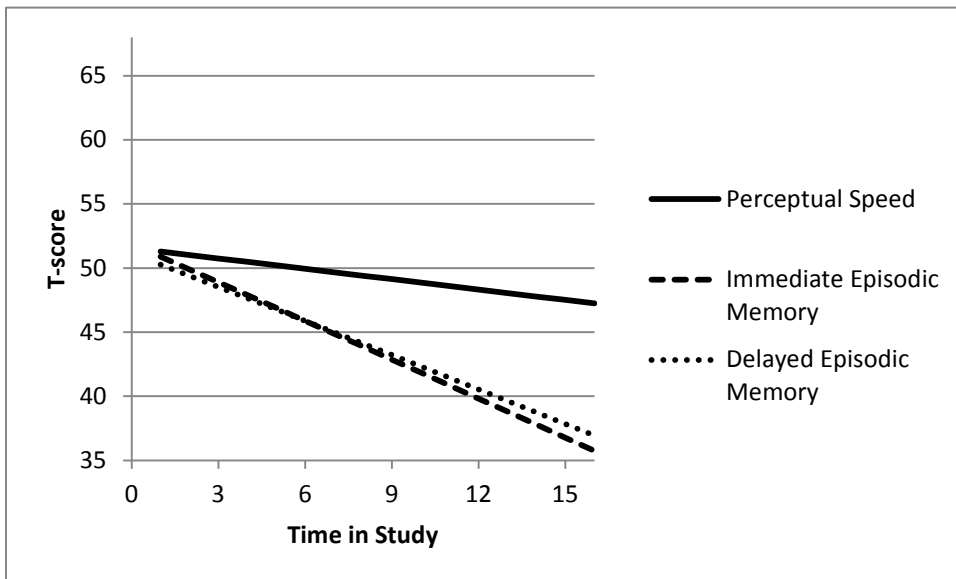
Figure 1 – Model-implied change in activity score (part a) and cognitive ability (part b) over the study period.

Figure 2 - Standardized covariance estimates between cognitive activity and perceptual speed by age group. * $p < .05$. ** $p < .01$. *** $p < .001$.

Longitudinal associations between activity and cognition



(part A)



(part B)

Longitudinal associations between activity and cognition

