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ORIGINAL INVESTIGATION

Physical activity and cognitive functioning in the oldest old: within- and between-person cognitive activity and psychosocial mediators

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Abstract The current study examines the role of social contact intensity, cognitive activity, and depressive symptoms as within- and between-person mediators for the relationships between physical activity and cognitive functioning. All three types of mediators were considered simultaneously using multilevel structural equations modeling with longitudinal data. The sample consisted of 470 adults ranging from 79.37 to 97.92 years of age (M = 83.4; SD = 3.2) at the first occasion. Between-person differences in cognitive activity mediated the relationship between physical activity and cognitive functioning, such that individuals who participated in more physical activities, on average, engaged in more cognitive activities and, in turn, showed better cognitive functioning. Mediation of between-person associations between physical activity and memory through social contact intensity was also significant. At the within-person level, only cognitive activity mediated the relationship between physical activity and change in cognition; however, the indirect effect was small. Depressive symptomatology was not found to significantly mediate within- or between-person effects on cognitive change. Our findings highlight the implications of physical activity participation for the prevention of cognitive decline and the importance of meditational processes at the between-person level. Physical activity can provide older adults with an avenue to make new friendships and engage in more cognitive activities which, in turn, attenuates cognitive decline.

Keywords Physical activity · Cognitive decline · Aging · Social support · Cognitive activity · Depression · Mediation · Multilevel structural equation modeling

Physical activity has been found to be an important factor that can account for and may modify aging-related cognitive decline (Busse et al. 2009; Colcombe and Kramer 2003; Kramer et al. 2006). In addition to the relationship between physical activity and cognitive aging, physical activity has also been found to improve other psychosocial variables (Morgan and Bath 1998; Strawbridge et al. 2002; Vance et al. 2005). Furthermore, these psychosocial variables have also been linked with cognitive aging. For example, longitudinal studies suggest that engaging in various lifestyle activities—such as cognitive, physical, and social activities—attenuates cognitive decline (Bielak et al. 2007; Ghisletta et al. 2006; Lindwall et al. 2012; Mitchell et al. 2012; Small et al. 2012; van Gelder et al. 2004), highlighting the intertwined relationship between physical, psychosocial, and cognitive variables. More studies are needed to further explain the

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mechanisms by which physical activity enhances cognitive functioning (Miller et al. 2012; Vance et al. 2005). Although previous studies have focussed on the direct relationship between lifestyle changes and cognitive functioning, an indirect relationship between physical activity and cognitive functioning is also possible. However, little research thus far has examined the role of such potential mediators on the influence of physical activity on cognitive decline (Miller et al. 2012).

The projected increase in the proportion of the oldest old (United Nations, Department of Economic and Social Affairs, Population Division 2013) has resulted in additional interest on better understanding the aging process for adults 80 years of age and older. Most research on the mechanism by which physical activity enhances cognitive functioning has focused on the youngest old, although research suggests that the oldest old benefit from physical activity to a greater extent than younger adults (Hultsch et al. 1993; Bielak et al. 2007). More research that extends beyond the younger samples is needed.

Engaging in cognitively stimulating activities is one likely mediator of the relationship between physical activity and cognition, as those older adults who are more physically active may also engage in more cognitively stimulating activities, which in turn may attenuate cognitive decline. For example, by engaging in physical activities such as gardening, golf, and tennis, older adults are also engaging in cognitive activities. Participation in these activities may also result in increased reading (e.g., reading about gardening). In turn, engaging in cognitive activities may delay cognitive decline. To date, mixed results have been reported about the relationship between physical activity and cognitive functioning. One possible explanation for these mixed results is that many of these studies failed to account for cognitive activities. This aligns with recent intervention studies which found that participation in physical activity in combination with cognitive activity enhanced cognitive functioning, whereas engaging in purely physical activity failed to show significant results (Oswald et al. 2006). Sturman et al. (2005) reported that engaging in physical activity at baseline was related to a slower rate of decline in cognitive functioning. However, they also found that the relationship between physical activity and cognition was no longer significant once participation in cognitively stimulating activities was accounted for (Sturman et al. 2005). One explanation for this finding is that physical activity does not protect against cognitive decline once cognitive activity is accounted for. However, an alternative explanation is that engagement in physical activity indirectly has an effect on cognitive functioning through its effect on cognitive activity, such that more physical activity leads to more cognitive activity which, in turn, leads to improved cognitive functioning.

Social support is another potential mediator of the relationship between physical activity and cognitive functioning that deserves to be further examined. Numerous different facets of social support have been documented including aspects of social relationships which focus on social contact intensity (e.g., number of people with whom the respondent has contact; Brissette et al. 2000). Older adults who participate in more physical activity may have access to a larger network size given that physical activity promotes contact with others (Vance et al. 2005). For example, engaging in more physical activities such as walking and aerobic exercise may lead to more contact with friends and family. In turn, greater social contact leads to improved cognitive aging (Barnes et al. 2004; Bassuk et al. 1999; Bennett et al. 2006; Fratiglioni et al. 2000; Hughes et al. 2008). This aligns with the social-stimulation hypothesis which suggests that physical activity increases social contact which results in increased mental stimulation and improved cognitive functioning (Vance et al. 2005). Social contact intensity is also related to improved physical and psychological health (e.g., increased self-efficacy and self-esteem), which can lead to improved cognitive functioning (Bassuk et al. 1999; Seeman et al. 1996). These studies highlight the intertwined relationship between physical activity, social contact intensity, and cognitive functioning. However, other studies have failed to find a positive effect of social contact on cognitive functioning (Albert et al. 1995) and others have found mixed results (Brown et al. 2012). Mediation analysis of longitudinal data may allow us to further explore the process by which physical activity indirectly affects cognitive functioning through social contact intensity.

Another important predictor of cognitive functioning that has received much attention is depression. Numerous studies report the benefits of exercise on mental health (Morgan and Bath 1998; Strawbridge et al. 2002). In turn, other studies have also reported the negative impact of depression on cognitive functioning (Yaffe et al. 1999). Given the evidence that depression can lead to cognitive decline (Comijs et al. 2001; Bassuk et al. 1998), the positive effect of physical activity on depression is one possible mechanism by which physical activity enhanced cognitive functioning (depression-reduction hypothesis; Khatri et al. 2001, Vance et al. 2005). It is possible that physical activity has an indirect effect on cognitive functioning through its effect on older adults' mental health. Longitudinal mediation models are needed to further untangle the complex relationship between physical activity, depression, and cognition.

The majority of the aforementioned studies evaluate each predictor separately. One study did examine the role of physical activity (walking and gardening), social contact (participation in recreation and social centers, social activities, and voluntary activities), and cognitive activities (reading) in predicting cognitive functioning (MMSE) and found that all predictors were significant (Gallucci et al. 2009). However, this study was cross-sectional and did not examine indirect effects. It is important to better understand how these variables interrelate as predictors and mediators and which are more strongly related to cognitive outcomes. Although some researchers have included many psychosocial and cognitive factors into one analysis, the majority have done so by combining a variety of individual items into one global index of everyday activities or general lifestyle (Bielak et al. 2012; Hultsch et al. 1999; Lövdèn et al. 2005; Mackinnon et al. 2003; Newson and Kemps 2005). Although this approach can be valuable, it does not distinguish which type of activity is more strongly associated with cognitive decline. Nonsignificant results might be due to a limited number of items in a subarea that would normally have been significant had it been measured in isolation (Hultsch et al. 1999).

In addition, few studies have compared within-person (how each individual changes) and between-person (interindividual differences in change) results. How these differ is important given that the inferences we make from cross-sectional studies may not align with those we would make using longitudinal data (Cole and Maxwell 2003; Hofer et al. 2006; Hofer and Sliwinski 2001; Lindenberger and Pötter 1998; Maxwell and Cole 2007; Maxwell et al. 2011). Furthermore, studies rarely decompose within- and between-person effects, so results that may have been interpreted as within persons have generally represented a mix of within- and between-person effects. The few studies that have compared between- and within-person effects have found differences between the levels (Bielak et al. 2012; Brown et al. 2012; Lindwall et al. 2012; Mitchell et al. 2012). For example, Lindwall et al. (2012) examined the relationship between physical activity and cognitive functioning using a multilevel growth model and found a positive within-person relationship between physical activity and cognitive functioning but no between-person relationship using baseline physical activity. Similarly, Mitchell et al. (2012) found a positive within-person relationship between cognitively stimulating activities and cognitive decline but no between-person relationship.

The current paper evaluates the role of social contact intensity, engagement in cognitive activities, and depressive symptoms as mediators of the within- and between-person effects of physical activity on cognitive functioning in a sample of adults 80 years of age and older. We hypothesize that social contact intensity, engagement in cognitive activities, and depressive symptoms will mediate the within- and between-person relationships between physical activity and cognitive functioning. The investigation of indirect effects of the relations between physical activity and cognitive decline with concurrent evaluation of within- and between-person effects will be addressed using multilevel structural equation modeling (MSEM) which simultaneously allows for indirect effects at both the between- and within-person levels of analysis (Preacher et al. 2010; Zhang et al. 2009).

Method

Origins of variance in the oldest old (OCTO-Twin)

The OCTO-Twin study included dizygotic (DZ) and monozygotic (MZ) twin pairs aged 80 years of age and older (Johansson et al. 2004; McClearn et al. 1997). The sample was selected from older adults in the population-based Swedish Twin Registry (Cederlof and Lorich 1978). Older adults participating in the study were tested in their residence by nurses (McClearn et al. 1997). Informed consent was obtained from each participant. Five cycles of longitudinal data were collected at 2-year intervals. The initial sample consisted of 702 individuals (351 same-sex pairs). Individuals who were diagnosed with dementia over the course of the study ($n = 225$) were excluded from the analyses presented in this manuscript. One of the covariates, education, had seven cases with missing data that were also removed from the analyses. The final sample consisted of 470 individuals 165 (35.1 %) males, and 305 (64.9 %) females, ranging from 79.37 to 97.92 years of age at the first occasion. Included were 172 pairs of twins and 126 older adults who no longer had their twin included in the sample. They had an average of 7.3 years of education and reported a mean self-rated health score of 6.99 (SD = 1.9) out of a possible score of 12 with higher scores representing better self-rated health. The rate of attrition was between 15 and 27 % every 2 years, mostly due to death (see Table 1). Descriptive statistics for each occasion are provided in Table 1, and correlations among all variables at Time 1 are provided in Table 2. For the correlation matrix among all variables at each occasion, please contact the corresponding author.

Measures

Assessment of cognitive performance

Processing speed A modified version of the Digit-Symbol Substitution Test (verbal rather than written) was used to assess processing speed of participants (Wechsler 1991). Participants were given a record form with symbol-digit pairs followed by a series of digits. The participants were asked to provide a verbal response of the matching digit under each of the provided symbols as quickly as possible

Table 1 Descriptive statistics for study variables

Variables	Baseline Mean (SD)	Year 2 Mean (SD)	Year 4 Mean (SD)	Year 6 Mean (SD)	Year 8 Mean (SD)	ICC	*r* T1–T2	*r* T1–T5
OCTO-Twin								
Sample (% retention)	470 (100)	401 (85.3)	293 (73.1)	222 (75.8)	174 (78.4)	–	–	–
Age	83.4 (3.2)	85.4 (3.1)	87.1 (2.8)	88.9 (2.8)	90.7 (2.4)	.46	–	–
Speed (DS)	25.5 (10.7)	26.0 (10.3)	26.5 (10.7)	26.1 (10.7)	23.5 (10.4)	.71	.78	.60
Spatial visual. (BD)	12.1 (7.1)	12.7 (6.7)	12.7 (6.6)	12.2 (6.8)	11.4 (6.9)	.74	.77	.71
Knowledge (I)	29.3 (10.4)	30.5 (10.0)	30.0 (10.8)	29.9 (11.2)	27.5 (10.5)	.83	.87	.72
Memory (PR)	10.0 (4.0)	10.5 (3.6)	10.5 (3.6)	10.9 (3.4)	10.1 (3.5)	.66	.64	.50
Social contact	3.0 (1.0)	3.0 (.95)	3.1 (.89)	3.0 (.99)	2.8 (.92)	.39	.45	.36
Depression(CES-D)	13.8 (5.7)	13.8 (5.0)	13.6 (4.3)	14.0 (4.8)	14.1 (4.8)	.41	.43	.24
Cognitive activity	2.2 (1.8)	1.9 (1.7)	1.5 (1.5)	1.4 (1.4)	1.2 (1.3)	.54	.66	.44
Physical activity	0.7 (.7)	0.9 (.7)	0.9 (.7)	0.7 (.7)	0.6 (.6)	.42	.54	.27

OCTO-Twin Origins of variance in the oldest old, *% retention* is from the previous time point, *I* Information, *DS* Digit-symbol, *BD* Block design, *Spatial Visual* Spatial visualization, *PR* Prose recall, *CES*-D Center for Epidemiological Studies-depression scale, *SD* Standard deviation, *ICC* Intraclass correlations, *r* Correlation

Table 2 Correlations among study variables at time 1

	Memory (P)	Spatial visual (BD)	Knowledge (I)	Speed (DS)	Cognitive activity	Depression (CES-D)	Social contact	Physical activity
Memory (PR)	–							
Spatial visual (BD)	.45**	–						
Knowledge (I)	.54**	.39**	–					
Speed (DS)	.52**	.62**	.49**	–				
Cognitive activity	.33**	.37**	.41**	.41**	–			
Depression (CES-D)	.02	−.14**	.002	.00	−.08	–		
Social contact	.16**	.18**	.13**	.23**	.24**	−23**	–	
Physical activity	.16**	.12*	.10*	.20**	.27**	−.14**	.12*	–

I Information, *DS* Digit-symbol, *BD* Block design, *Spatial Visual* Spatial visualization, *PR* Prose recall, *CES-D* Center for Epidemiological Studies-depression scale

* $P > 0.05$

** $P > 0.01$

without skipping any numbers. Participants were given two 90-second trials to complete the task and received one point for every correctly matched symbol.

Spatial visualization Kohs block design test (Dureman and Salde 1959) was used. Respondents were shown cards with designs and were instructed to replicate the patterns using colored blocks. Seven cards with white and red patterns were given to the participants, each with a maximum score of six, depending on the speed and accuracy of the solution. A score of zero was given if the allotted time was surpassed. The maximum score was 42.

Knowledge A Swedish version of the information task (Jonsson and Molander 1964) derived from the Wechsler adult intelligence scale (WAIS; Wechsler 1981) was used. Participants were asked general knowledge questions. The maximum score was 44.

Verbal memory The prose recall test was used. Respondents were read a humorous story (100 words) and were instructed to freely recall the words from the narrative (Johansson et al. 1992). A coding system similar to the Wechsler memory test (Wechsler 1945) was used where respondents were scored based on the amount of information they recalled. The maximum score was 16.

Depressive symptoms Depressive symptoms were assessed using the 20-item Center for Epidemiological Studies-Depression scale (CES-D; Radloff 1977). The CES-D is not a clinical diagnostic tool. Rather it is designed to assess possible depressive symptoms and to examine whether these symptoms relate to other variables. Participants were asked how frequently they experienced each item on a 4-point scale, ranging from "rarely or none of the time" to "most or all of the time" (Haynie et al. 2001). Four of the 20 items were reversed in order to align with the 16 negatively worded items (Haynie et al. 2001). Therefore, higher scores indicated a greater number of depressive symptoms.

Social contact intensity Participants were asked "How many people do you see?" at each occasion. Response options included: "none," "1–2," "3–5," "6–10," or "11 or more." The single item social contact measure was developed specifically for use in the OCTO-Twin study.

Cognitive activity Cognitive activity was assessed with six self-report items about their engagement in games, crosswords, literature, writing, studies, and other mental activities with response items being rated as "no"(0) or "yes"(1). One additional item also asked participants "Do you do anything in particular to train your memory or keep your mind active?" with a response option of "no" (0), "yes, to a certain degree" (1), or "yes, definitely" (2). Composite scores of the seven items were created at each wave and ranged between 0 and 8. The cognitive activity measure was developed specifically for use in the OCTO-Twin study.

Physical activity Present levels of physical activity were measured by asking respondents: Are you presently doing or have you previously done anything special to train your body or "keep your body fit"? Response options were "no" (0), "yes, to some extent" (1) or "yes, to a great extent" (2). Respondent provided a response for their present level as well as their past level of physical activity, but the current paper only uses present levels. The item "Keeping the body fit" in Swedish stands for keeping the body moving which strongly implies physical activity. The physical activity measure was developed specifically for use in the OCTO-Twin study.

Covariates We adjusted for years of age, education, and sex in all analyses. Years of education is important to adjust in these analyses as previous studies have found education to be predictive of cognitive functioning to a greater extent than other predictors including social support and depression (Zelinski and Gilewski 2003). Sex (male = 0; female = 1) was included as a covariate at the between-person level. Age was also decomposed into within- and between-person effects by regressing physical activity, cognitive activity, social contact intensity, depressive symptoms, and the cognitive outcomes on age at the within- and between-person level.

Dementia In order to identify individuals with dementia at each wave, multidisciplinary group consensus conferences used expertise from various disciplines to reach consensus about diagnosis and differential diagnosis, taking into account other health-related conditions. DSM–III–R criteria for dementia (American Psychiatric Association 1987), NINCDS-ADRDA criteria for Alzheimer's disease (McKhann et al. 1984), and NINDS-AIREN criteria for vascular dementia (Roman et al. 1993) were used.

Statistical analyses

We used Muthén and Asparouhov's (2008) approach to MSEM and applied it to mediation analysis as suggested by Preacher et al. (2010). MSEM is different from MLM in that the between-person and within-person variance in each variable is partitioned directly by the model, rather than by observed variables as in person-mean centering (e.g., level-2 means to represent between-person variance; level-1 person-mean deviations to represent within-person variance). In MSEM, regression paths among the variables are included at level 1 (within persons) and at level 2 (between persons), allowing examination of indirect effects for both within and between components, each controlling for the other. When all of the variables are measured at level 1, the model is referred to as 1-1-1 MSEM (Preacher et al. 2010). For example, the effects of physical activity on social contact intensity, physical activity on memory, and social contact intensity on memory can be included at level 1 and at level 2, given that these variables all change as a function of time and that they all differ between individuals (This is an example of 1-1-1 MSEM). The MSEM approach takes advantage of both MLM (focus on the differentiation between level 1 and level 2 components) and SEM (a single variable can be both a predictor and an outcome) features to modeling longitudinal data (Mehta and Neale 2005; Preacher et al. 2010). See Fig. 1 for an illustration of the model used in the current paper.

Mplus version 6.11 was used for fitting the MSEM models (Muthén and Muthén 1998–2011). The two-level option was used in order to model the random intercepts and fixed slopes using the multilevel framework. Given that twin data were used, we employed cluster identifiers to account for the dependency among sample participants (Stapleton 2006). Using TYPE = COMPLEX with CLUSTER, standard errors and χ^2 tests of model fit take into account the non-independence of observations due to the cluster sampling of twin data (Muthén and Muthén 1998–2010). Mplus uses the full information maximum likelihood estimator to include missing data of endogenous

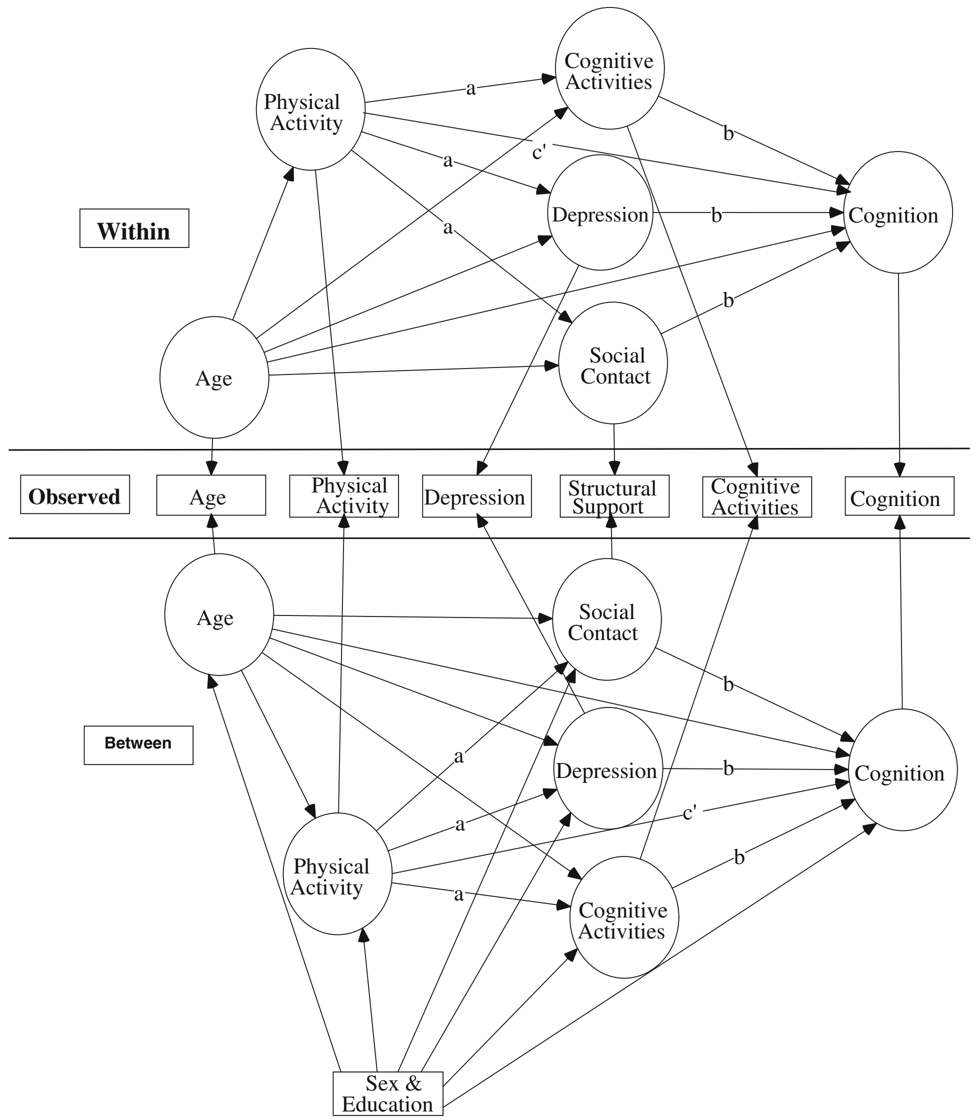

Fig. 1 Illustration of the 1-1-1 MSEM model. *Single headed arrows* = fixed effects. For simplicity reasons, covariances between latent variables are not depicted but were estimated in the models. *a* X → M, *b* M → Y, *c′* X → Y

variables under the missing at random assumption. Robust maximum likelihood (MLR) estimation was used (Muthén and Muthén 1998–2010) to provide adjusted χ^2 and standard errors that account for non-normality. Since the delta method confidence intervals provided by Mplus may be inaccurate for the indirect effects and given the lack of normality in the sampling distribution for indirect effects (Bielak 2010; Preacher et al. 2010), a Monte Carlo web utility developed by Selig and Preacher (2008) was used to provide indirect effects in MSEM.

Intraclass correlations (ICC) were calculated to make sure enough between-person variance was available to warrant decomposing the level 1 and level 2 variance (Hoffman and Stawski 2009; Preacher et al. 2010; Singer and Willett 2003). Including the between portion of the model with ICCs below .05 can result in biased results and in convergence difficulties (Preacher et al. 2010). As shown in Table 1, all ICC values were >.4, indicating substantial between-person variation in each variable. Accordingly, direct and indirect effects at both the within- and between-person levels of the model were simultaneously estimated. The direct effects of age at the within- and between-person level were also estimated. Intercepts were adjusted for sex and education. The within- and between-levels of this MSEM model are each saturated (i.e., no degrees of freedom remain), such that model fit indices would have indicated no discrepancy between the observed and model-predicted covariances among the variables whose level-2 and level-1 variance were partitioned by the maximum likelihood algorithm.

Effect size

κ^2 values of effect size were used. This measure of effect size is recommended by Preacher and Kelley (2011) above all other measures. κ^2 is the ratio of the indirect effect in comparison to the maximum possible effect size (Preacher and Kelley 2011). By creating upper and lower boundaries for *a* (X → M; e.g., physical activity → social contact intensity), *b* (M → Y; e.g., social contact intensity → memory), and *ab* (e.g., physical activity → social contact intensity * social contact intensity → memory), we are able to provide a measure of the effect size of the indirect effect by comparing the model estimated indirect effect to the maximum possible effect (Preacher and Kelley 2011). See Preacher and Kelley (2011) for the equations used to calculate indirect effect size. To facilitate interpretation, the ratios were described as small (.01) medium (.09) or large (.25) based on the guidelines from Cohen (1988); see Preacher and Kelley (2011).

Results

Within-person direct effects

Age effects

All models first accounted for change in physical activity, cognitive activity, social contact intensity, depression, speed, and a range of cognitive functions as a function of advancing age such that all other effects are unique effects after controlling for age. All cognitive outcomes (with the exception of memory), cognitive activity, and social contact intensity were found to decline significantly as a function of age, whereas depression increased as a function of age. Results, including unstandardized estimates, and p-values for all direct and indirect effects, as well as corresponding 95 % confidence intervals, are provided in Tables 3, 4.

X → Y (path c′)

After controlling for the aging effect on physical, social, and cognitive activities, depression, and cognitive functioning, within-person associations between physical activity and knowledge and speed were found, such that occasion-specific decreases in physical activity were associated with occasion-specific decreases in knowledge and speed. No significant within-person relation was found between physical activity and spatial visualization or memory (see Table 3, 4).

X → M (path a)

A significant within-person association between physical activity and cognitive activity was found, such that cognitive activity was greater on occasions where physical activity participation was also higher. However, there were no associations between physical activity and either social contact intensity or depression at concurrent occasions (see Table 3, 4).

M → Y (path b)

Within-person decreases in cognitive activity were associated with occasion-specific decreases in knowledge, but a within-person change in cognitive activity was not predictive of within-person changes in memory, spatial visualization, or speed. Within-person changes in depression failed to predict within-person changes in memory, speed, spatial visualization, and knowledge. However, even after controlling for age effects, a significant within-person association was found between social contact intensity and memory, speed, spatial visualization, and knowledge, such that cognitive functioning scores were higher on occasions in which social contact intensity was also higher.

Within-person indirect effects

Only the within-person indirect effect of physical activity on knowledge through cognitive activity was found to be significant. Within-person changes in cognitive activity mediated the relationship between physical activity and cognitive change, more specifically knowledge. However, the effect size was small ($\kappa^2 = .01$). No other within-person indirect effects were significant. Within-person residuals were significant for all outcome variables suggesting that variance remains unexplained.

Between-person direct effects

Covariates (sex and education)

Females were more likely to report more cognitive activity and a greater number of symptoms of depression and to score lower on the knowledge and higher on the memory test. Sex was not associated with social contact intensity, speed, spatial visualization, or physical activity. Higher education was associated with higher memory, spatial visualization, knowledge, speed, cognitive activity, and depression, but education was not associated with social contact intensity (see Tables 3, 4).

Age effect

Between-person differences in age were not associated with between-person differences in any of the cognitive outcome variables.

X → Y (path c′)

After accounting for the effects of the between-person covariates, between-person differences in physical activity failed to predict between-person differences in memory, spatial visualization, speed, and knowledge.

Table 3 Unstandardized estimates and standard errors for the MSEM models

Models	Spatial visualization (block design)					Processing speed (digit-symbol)				
	Est. (κ^2)	SE	*P*	95 % CI		Est. (κ^2)	SE	*P*	95 % CI	
				Lower	Upper				Lower	Upper
Within-person effect										
Age → Cog	−0.27	0.05	<.0001	−0.37	−0.18	−0.46	0.09	<.0001	−0.69	−0.28
Age → physical	−0.03	0.007	<.0001	−0.05	−0.02	−0.03	0.007	<.0001	−0.05	−0.02
Age → social	−0.05	0.009	<.0001	−0.07	−0.04	−0.05	0.009	<.0001	−0.07	−0.04
Age → Dep	0.10	0.05	.046	0.002	0.20	0.10	0.05	.046	0.002	0.20
Age → CogAct	−0.18	0.01	<.0001	−0.20	−0.15	−0.18	0.01	<.0001	−0.20	−0.15
Physical → social (a)	0.08	0.04	.07	−0.007	0.16	0.08	0.04	.07	−0.007	0.16
Physical → Dep (a)	−0.38	0.28	.18	−2.78	0.74	−0.38	0.28	.18	−2.78	0.74
Physical → CogAct (a)	0.22	0.07	.001	0.09	0.35	0.22	0.07	.001	0.09	0.35
Physical → Cog (c′)	0.37	0.20	.07	−0.03	0.77	1.16	0.38	.002	0.19	1.91
Social → Cog (b)	0.49	0.17	.003	0.17	0.81	0.65	0.30	.03	0.06	1.23
Dep → Cog (b)	−0.05	0.03	.13	−0.11	0.02	0.03	0.05	.55	−0.07	0.14
CogAct → Cog (b)	0.09	0.11	.46	−0.14	0.31	0.17	0.21	.42	−0.36	0.57
Indirect social	0.04 (.006)	0.03	.14	−0.004	0.10	0.05 (.005)	0.03	.15	−0.008	0.14
Indirect Dep	0.02 (.003)	0.02	.33	−0.01	0.07	−0.01 (.001)	0.021	.61	−0.07	0.03
Indirect CogAct	0.02 (.003)	0.02	.30	−0.03	0.08	0.04 (.003)	0.05	.43	−0.05	0.14
Between-person effect										
Intercept age	85.43	0.26	<.0001	84.91	85.95	85.43	0.26	<.0001	84.91	85.94
Intercept Cog	19.39	14.19	.17	−8.42	47.21	31.98	21.53	.14	−10.21	74.17
Intercept CogAct	1.33	2.60	.61	−3.76	6.42	1.38	2.58	.59	−3.67	6.43
Intercept physical	0.97	1.06	.36	−1.12	3.05	0.98	1.07	.36	−1.12	3.07
Intercept social	4.57	1.42	.001	1.80	7.35	4.60	1.42	.001	1.82	7.39
Intercept CESD	24.23	8.23	.003	8.11	40.35	24.06	8.23	.003	7.92	40.19
Age → Cog	−0.14	0.16	.38	−0.45	0.17	−0.21	0.24	.39	−0.67	0.26
Age → physical	−0.002	0.01	.88	−0.03	0.02	−0.002	0.01	.88	−0.03	0.02
Age → social	−0.02	0.02	.19	−0.05	0.01	−0.02	0.02	.18	−0.05	0.01
Age → Dep	−0.11	0.10	.25	0.002	−0.30	−0.08	0.10	.25	−0.30	0.08
Age → CogAct	−0.009	0.03	.78	−0.07	0.05	−0.009	0.03	.77	−0.07	0.05
Physical → social (a)	0.32	0.10	.001	0.13	0.50	0.31	0.10	.001	0.13	0.50
Physical → Dep (a)	−1.76	0.52	.001	−2.78	−0.74	−1.76	0.52	.001	−2.78	−0.74
Physical → CogAct (a)	0.85	0.16	<.0001	0.53	1.16	0.84	0.16	<.0001	0.53	1.16
Physical → Cog (c′)	−0.25	0.80	.76	−1.82	1.32	0.70	1.31	.59	−1.87	3.26
Social → Cog (b)	1.47	0.67	.03	0.16	2.78	1.71	1.07	.11	−0.38	3.80
Dep → Cog (b)	−0.26	0.12	.03	−0.12	−0.01	−0.11	0.20	.59	−0.49	0.28
CogAct → Cog (b)	2.16	0.37	<.0001	1.43	2.90	3.27	0.54	<.0001	2.21	4.33
Indirect social	0.46 (.04)	0.26	.07	0.04	1.06	0.54 (.03)	0.36	.14	−0.12	1.39
Indirect Dep	0.46 (.03)	0.25	.07	0.02	1.05	0.17 (.009)	0.35	.62	−0.50	0.93
Indirect CogAct	1.83 (.14)	0.46	<.0001	0.98	2.83	2.76 (.12)	0.69	<.0001	1.53	4.25

Parametric bootstrap confidence intervals based on the Monte Carlo method were obtained for the indirect effects

N 470, *Cog* Cognitive functioning, *Dep* Depression, *CogAct* Cognitive activity, *Est.* Unstandardized estimates, *SE* Standard errors, *P* Probability value, *CI* Confidence intervals, κ^2 Effect size for indirect effect, *a* Direct path from predictor to mediator, *b* Direct path from mediator to outcome variable, *c′* Direct path from predictor to outcome variable after controlling for the mediators

Table 4 Unstandardized estimates and standard errors for the MSEM models

Models	Verbal memory (prose)					Knowledge (information task)				
	Est. (κ^2)	SE	*P*	95 % CI		Est. (κ^2)	SE	*P*	95 % CI	
				Lower	Upper				Lower	Upper
Within-person effect										
Age → Cog	−0.06	0.04	.08	−0.13	0.007	−0.32	0.06	<.0001	−0.20	−0.15
Age → physical	−0.03	0.007	<.0001	−0.05	−0.02	−0.03	0.007	<.0001	−0.05	−0.02
Age → social	−0.53	0.009	<.0001	−0.07	−0.04	−0.05	0.009	<.0001	−0.07	−0.04
Age → Dep	0.10	0.05	.046	0.002	0.20	0.10	0.05	.046	0.002	0.20
Age → CogAct	−0.18	0.01	<.0001	−0.20	−0.15	−0.18	0.01	<.0001	−0.20	−0.15
Physical → social (a)	0.08	0.04	.07	−0.007	0.16	0.08	0.04	.07	−0.007	0.16
Physical → Dep (a)	−0.38	0.28	.18	−2.78	0.74	−0.38	0.28	.18	−2.78	0.74
Physical → CogAct (a)	0.22	0.07	.001	0.10	0.35	0.22	0.07	.001	0.10	0.35
Physica → Cog (c′)	0.11	0.18	.52	−0.23	0.46	0.64	0.24	.006	0.18	1.11
Social → Cog (b)	0.30	0.12	.01	0.07	0.54	0.75	0.19	<.0001	0.26	1.13
Dep → Cog (b)	−0.004	0.02	.88	−0.05	0.03	−0.03	0.04	.42	−0.11	0.05
CogAct → Cog (b)	0.14	0.08	.08	−0.02	0.30	0.41	0.15	.007	0.11	0.70
Indirect Social	0.02 (.006)	0.02	.12	−0.003	0.06	0.06 (.007)	0.04	.10	−0.004	0.14
Indirect Dep	0.001 (.0007)	0.009	.88	−0.02	0.03	0.01 (.001)	0.02	.47	−0.02	0.06
Indirect CogAct	0.01 (.007)	0.02	.46	−0.004	0.08	0.09 (.01)	0.04	.03	0.02	0.19
Between-person effect										
Intercept age	85.43	0.26	<.0001	84.91	85.95	85.43	0.26	<.0001	84.91	85.94
Intercept Cog	7.74	7.62	.31	−7.20	22.67	63.17	20.79	.002	22.43	103.91
Intercept CogAct	1.47	2.60	.57	−3.62	6.56	1.64	2.60	.53	−3.56	6.74
Intercept physical	0.99	1.06	.35	−1.10	3.07	0.96	1.07	.37	−1.13	3.05
Intercept social	4.67	1.42	.001	1.90	7.45	4.68	1.42	.001	1.89	7.46
Intercept CESD	23.91	8.23	.004	7.78	40.04	23.71	8.17	.004	7.70	39.72
Age → Cog	−0.04	0.08	.61	−0.21	0.12	−0.41	0.23	.08	−0.86	0.05
Age → physical	−0.002	0.01	.87	−0.03	0.02	−0.002	0.01	.89	−0.03	0.02
Age → social	−0.02	0.02	.17	−0.06	0.009	−0.02	0.02	.17	−0.06	0.009
Age → Dep	−0.11	0.10	.25	−0.30	0.08	−0.11	0.10	.25	−0.30	0.08
Age → CogAct	−0.01	0.03	.74	−0.07	0.05	−0.18	0.01	<.0001	−0.07	0.05
Physical → Social (a)	0.31	0.10	.001	0.13	0.50	0.32	0.10	.001	0.13	0.51
Physical → Dep (a)	−1.76	0.52	.001	−2.78	−0.74	−1.76	0.52	.001	−2.78	−0.74
Physical → CogAct (a)	0.84	0.16	<.0001	0.52	1.16	0.84	0.16	<.0001	0.52	1.16
Physical → Cog (c′)	0.70	0.47	.14	−0.23	1.61	−1.11	1.23	.37	−3.52	1.30
Social → Cog (b)	1.32	0.40	.001	0.53	2.11	0.85	1.02	.41	−1.15	2.84
Dep → Cog (b)	0.002	0.08	.98	−0.15	0.17	−0.20	0.20	.32	−0.59	0.19
CogAct → Cog (b)	0.41	0.21	.001	−0.01	0.83	2.57	0.55	<.0001	1.48	3.66
Indirect social	0.41 (.06)	0.17	.02	0.11	0.82	0.27 (.01)	0.33	.41	−0.38	1.04
Indirect Dep	−0.004 (.002)	0.14	.98	−0.32	0.28	0.34 (.01)	0.38	.36	−0.35	1.15
Indirect CogAct	0.34 (.05)	0.19	.07	−0.01	0.76	2.16 (.10)	0.65	.001	1.05	3.55

Parametric bootstrap confidence intervals based on the Monte Carlo method were obtained for the indirect effects

N 470, *Cog* Cognitive functioning, *Dep* Depression, *CogAct* Cognitive activity, *Est*. Unstandardized estimates, *SE* Standard errors, *P* Probability value, *CI* Confidence intervals, κ^2 Effect size for indirect effect, *a* direct path from predictor to mediator, *b* Direct path from mediator to outcome variable, c' Direct path from predictor to outcome variable after controlling for the mediators

$X \rightarrow M$ (path a)

After accounting for the effect of the covariates, between-person differences in physical activity were significantly associated with cognitive activity, social contact intensity, and depression. That is, cognitive activity and social contact intensity were higher, and depression scores were lower on average for respondents who reported engaging in more physical activity than others (see Tables 3, 4).

$M \rightarrow Y$ (path b)

After accounting for the effect of the covariates, between-person differences in cognitive activity predicted differences in knowledge, speed, and spatial visualization, such that more frequent cognitive activity on average was associated with higher functioning in these cognitive domains. The between-person association for cognitive activity and memory, however, was nonsignificant. Between-person differences in social contact intensity predicted between-person differences in memory, spatial visualization, speed, and knowledge with higher social contact intensity associated with higher cognitive scores. Higher depression scores predicted lower spatial visualization, but were not associated with memory, knowledge, and speed.

Indirect effects

For speed, knowledge, and spatial visualization, between-person effects of physical activity on cognitive functioning through cognitive activity were significant, such that between-person differences in cognitive activity mediated the relationship between physical activity and speed, knowledge, and spatial visualization. The effect sizes were medium for physical activity on speed ($\kappa^2 = .12$), knowledge ($\kappa^2 = .10$), and spatial visualization ($\kappa^2 = .14$) through cognitive activity. The between-person indirect effect of physical activity on memory through cognitive activity was nonsignificant. Between-person differences in physical activity on memory through social contact intensity were significant, such that individuals who participated in more physical activities on average had more contact with other people and, in turn, had higher memory scores compared to others. However, the effect size was small ($\kappa^2 = .06$). The other indirect paths through social contact intensity were nonsignificant. Depression was not a significant mediator. Between-person residuals were significant for all outcomes, suggesting that variance remains unexplained.

Discussion

The purpose of this study was to clarify the within- and between-person relationships between physical activity and cognitive functioning, with emphasis on the mediating effects of social contact intensity, cognitive activity, and depressive symptoms. This is the first study to explore indirect effects of the relationship between physical activity and cognitive functioning by including multiple mediators simultaneously across multiple types of cognitive variables over an extended period of time. This is an advantage given that some cognitive variables are more highly associated with physical activity than others (Colcombe and Kramer 2003), and cognitive and psychosocial variables may act as mediators for only some outcomes. Another key advantage of this paper is that both within- and between-person effects were examined simultaneously allowing for a clearer decomposition of indirect effects at both levels. This is especially important given our finding of different effects across levels.

Within-person effects

Our study suggests that, at the within-person level, only cognitive activity mediates the relationship between physical activity and cognitive decline, and it does so only for the knowledge task. On occasions where older adults participated in less physical activity, they also engaged in fewer cognitive activities and, in turn, had lower scores on the information task. However, the effect size was small ($\kappa^2 = .01$), suggesting that the effect may not be of substantive importance. Occasion-specific changes in social contact intensity and depressive symptomatology were not found to mediate the relationship between physical activity and cognitive functioning.

A closer look at the direct effects further elucidates the relationship between the physical, psychosocial, and cognitive variables at the within-person level. First, cognitive functioning (with the exception of memory) and participation in cognitive and physical activity declined as a function of age, whereas depressive symptomatology increased as a function of age (although this within-person effect of age on depressive symptomatology had a p value of .048). This suggests that, after controlling for between-person differences, increasing age is associated with declines in social contact intensity, physical and cognitive activity, and cognitive performance, and an increase in depression. After controlling for the effects of age changes on physical activity, only the direct effect of physical activity on cognitive activity (path a) and social contact intensity on all cognitive outcomes (path b) was significant. Furthermore, within-person changes in physical activity were related to occasion-specific changes in the information task and processing speed but not memory or spatial visualization (path c'). These findings align with other studies which support the protective effect of physical activity and cognitive activity on cognitive decline (Albert et al. 1995). The finding that physical activity and social contact intensity was only related to some cognitive outcomes appears to vary from one study to the next (see review by Bielak 2010). Our finding that physical activity and social contact intensity attenuated decline in processing speed is not surprising and aligns with previous studies (Lövdèn et al. 2005; Newson and Kemps 2005). Given that processing speed is a cognitive variable affected by the aging process, it makes sense that lifestyle changes in older adults would result in greater improvement for that cognitive domain (Bielak 2010; Ghisletta et al. 2006). More studies that include different cognitive outcomes are needed to untangle the effect of physical activity on cognitive functioning. Engaging in cognitive activities was not related with cognitive functioning at the within-person level suggesting that engaging in these activities at each occasion does not impact cognitive functioning at that same occasion. Interestingly, a very different result was found at the between-person level. Overall, the current findings suggest that, after adjusting for the effect of age, changes in social contact intensity, depressive symptomatology, and cognitive activity at each occasion do not mediate the dynamic within-person relationship between physical activity and cognitive functioning.

Between-person effects

At the between-person level, the indirect effect of physical activity on cognitive functioning through cognitive activity was more prominent. Furthermore, the effect sizes were in the medium range suggesting more substantive importance than the within-person effect. Individuals who reported more physical activity, on average, when compared to other people were also more likely to engage in cognitively stimulating activities and, in turn, to perform better on the spatial visualization, processing speed, and information tests, but not on the memory task. In contrast, social contact intensity mediated the relationship between physical activity and memory, such that older adults who reported more physical activity on average also had more frequent social contacts and, in turn, performed better on the memory task. Depression was not a significant mediator.

As for direct between-person effects, older adults who participated in more physical activities, on average, were also more likely to engage in more cognitive activities, have more social contacts, and show fewer symptoms of depression. In addition, individuals who engaged in more cognitive activity on average scored higher on all cognitive outcomes, while those who reported more social contact scored more highly on memory and visuospatial abilities. The size of social networks has also been found to have a direct effect on cognitive functioning in other studies (Arbuckle et al. 1992). In general, individuals with fewer symptoms of depression showed better visuospatial abilities, albeit this effect was weak. However, between-person differences in physical activity were not associated with cognitive functioning. This aligns with previous research which examined within- and between-person effects separately and found no between-person effect of physical activity on cognitive functioning (Lindwall et al. 2012). However, similarly to Lindwall et al. (2012) a within-person effect was found between physical activity and cognitive functioning. Comparing within- and between-person results also suggests that social contact intensity levels and cognitive activity participation over the course of many years (captured by the between-person results), rather than current levels (captured by the within-person results), mediate the relationship between physical activity and cognitive functioning.

Importantly, the direct relation between physical activity and cognitive functioning as well as the indirect effects appeared to vary depending on the cognitive outcome. This aligns with previous studies reporting mixed results. A recent mini-review concluded that more research was needed to better understand which types of activity improve which aspects of cognitive aging (Bielak 2010). Furthermore, differences in results at the within- or between-person level highlight the importance of decomposing both effects.

The lack of an effect of depression on cognitive functioning is unexpected given previous research suggesting that depression can increase the risk of cognitive decline (Chodosh et al. 2007; Dotson et al. 2008; Jorm 2001; Sachs-Ericsson et al. 2005). Still, other studies, some similarly using the CES-D (Dufouil et al. 1996), have also failed to find a relationship between depression and cognitive decline (Chen 1999; Dufouil et al. 1996; Henderson et al. 1997; Jajodia and Borders 2011). More recently, Neubauer et al. (2013) also failed to find a longitudinal relationship between depressive symptoms and cognitive decline. One possible explanation proposed by the authors is that the relationship between cognition and depression cannot be captured using continuous measure of depressive symptomatology and cognitive decline.

Between-person differences in age were not significantly related to differences in physical activity, frequency of cognitive activity, social contact intensity, depressive symptoms, or cognitive functioning. The fact that the OCTO-Twin study is relatively age-homogenous (80–92) likely explains why age differences in cognitive functioning were not found.

Limitations

Although the use of a longitudinal research design is a clear strength of the current study, using pre-existing longitudinal data limit researchers to using measures included in the longitudinal study. Therefore, one limitation of the current study is that we were constrained to using measures included in the OCTO-Twin study. Although most were validated measures, the social contact intensity, cognitive activity, and physical activity measures were developed specifically for the study. The measure of social contact intensity was self-reported and did not capture who the relationship was with (spouse vs neighbor) or the frequency of social interactions. Social desirability is also possible with self-report measures of social contact intensity and physical activity (Bielak 2010). The measure of physical activity was a single self-reported question with only three response options; similarly, the cognitive activity measure was based on dichotomous items. As mentioned, OCTO-Twin was conducted in Sweden; therefore, items were translated from Swedish to English for publication purposes. Some items (e.g., "keeping the body fit") are not a direct translation from Swedish to English. The item in Swedish represents keeping the body moving which strongly implies physical activity. Even though a valid measure that includes numerous specific physical activities would have been beneficial, it is difficult for large long-term studies to ask about a long list of physical activities given time constraints. A shorter measure would have been feasible; however, as discussed by Bielak (2010), measuring physical activity with a shorter list of specific activities means that activities not included in the list will be excluded even though these would qualify as sources of physical activity. Furthermore, the measure of physical activity used in the current study is advantageous for longitudinal studies because it is less affected by differences between cohorts (e.g., gardening vs. yoga; Bielak 2010).

Another limitation is that block design scoring is affected by speed of response, and thus other measures of spatial visualization may have shown different results. Another relevant issue is the extent to which practice effects may have biased the obtained within-person effects. The possibility of performance gains over time as a result of repeatedly taking the same test is pervasive across many areas of functioning, and such practice effects may be different across the various cognitive measures (Ferrer et al. 2005), across individuals.

The current paper also focused specifically on adults 80 years of age and older, whereas most studies to date have concentrated on younger samples of older adults. This is an advantage of the current study; however, whether these findings are generalizable to all older adults is unknown given that those who survive beyond age 80 are also likely those with better physical and mental health.

Reverse causation is also possible such that changes in cognitive functioning may be causing changes in physical activity or the relationship may be bidirectional (Hertzog et al. 1999; Hultsch et al. 1999; Schooler et al. 1999; Schooler and Mulatu 2001, Small et al. 2012). Using a bivariate latent class score model, Small et al. (2012) found a bidirectional dynamic relationship between lifestyle engagement and cognitive functioning. Given our two-year interval, we decided that it was acceptable to use concurrent occasions. Studies using longer-lagged intervals have found nonsignificant results (Bielak et al. 2012; Hultsch et al. 1999) when compared to studies using shorter intervals (Ghisletta et al. 2006). Along similar lines, it is also possible that social support increases adherence to participation in physical activity (Chogahara et al. 1998; Kramer et al. 2003). Still, two longitudinal studies using the dual change score model (DCSM; McArdle 2001; McArdle and Hamagami 2001) found that engagement in leisure activities and social support predicted cognitive change, whereas cognitive functioning did not have an effect on these variables (Ghisletta et al. 2006; Lövdèn et al. 2005).

A comprehensive understanding of the relationship between engagement in physical activity and cognitive functioning involves a number of variables not included in the current paper. We have accounted for three potential mediators; however, other variables have been proposed. For example, physiological changes that occur as a result of physical exercise (e.g., hormonal changes and cerebral blood flow), nutrition and diet, and stress may also act as mediators (Bielak 2010). Aerobic fitness has been examined as a potential mediator (cardiovascular fitness hypothesis); however, a recent meta-analysis failed to support the cardiovascular fitness hypothesis (Etnier et al. 2006). Colcombe et al. (2006) found that physical activity had an effect on gray matter volume in the frontal and temporal cortex stressing the important biological basis between physical activity and cognitive functioning. Further longitudinal studies which include self-report as well as brain imaging information are warranted to more thoroughly understand the complex biopsychosocial relationship between physical activity and cognitive functioning.

There is also the possibility that respondents with preclinical dementia were included in our samples (Sliwinski et al. 1996), which might have affected the mediation effects (Sliwinski and Buschke 1997). In order to limit this shortcoming, those with a dementia diagnosis at any point in OCTO-Twin were removed from the analyses. However, future research should examine the benefits of exercise and possible indirect pathways between physical activity and cognitive functioning for individuals living with dementia.

Although it theoretically makes sense to include the random (i.e., individually varying) effect of change in physical activity on the change in the mediators and the random effect of the mediator changes on the changes in the cognitive outcomes, the current study does not include random slopes. We attempted to include random slopes, however, the computational complexity of modeling numerous mediators simultaneously with random effects resulted in model non-convergence.

Conclusion

Our findings, based on a large sample of older adults spanning an eight-year period and a wide range of cognitive outcomes, highlight the importance of examining indirect effects of physical activity on cognitive aging through social contact and cognitive activity between but not within individuals. In general, older adults who engaged in more physical activity also reported more extended social contact intensity and a greater engagement in cognitive activities, and in turn showed better cognitive performance compared to those who reported less physical activity. However, once the effects of within-person aging were taken into account, changes in physical activity at each occasion did not appear to be related to cognitive functioning through psychosocial and cognitive mechanisms. Still, within-person changes in physical activity over time did have a positive impact on cognitive functioning, just not indirectly through the variables included in the current study. Another strength of our study is that it examined the integrated effect of psychosocial and cognitive factors simultaneously and called attention to the importance of including multiple factors in active aging initiatives. Our findings further support the implication of physical activity for the prevention of cognitive decline in older adults but also highlight the meditational processes. It is possible that physical activity functions as a gateway behavior (Nigg et al. 1999; Tucker and Reicks 2002) for engagement in cognitive activities and social contact. Further longitudinal research is needed to examine the potential gateway relationship between physical activity and other health-related behaviors. In sum, physical activity can provide older adults with an avenue to make new friendships and engage in more cognitive activities which, in turn, can attenuate cognitive decline.

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