Is day-to-day variability in cognitive function coupled with day-to-day variability in affect?

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A B S T R A C T

Intra-individual differences in cognitive function that occur reliably across repeated assessment occasions are thought to correspond to contemporaneous fluctuations in affect. However, the empirical evidence for this hypothesis is to date inconclusive. Here, a sample of 98 participants was recruited to complete tests of short-term memory, processing speed, and working memory, as well as rating daily their positive and negative affect (PANAS), on each of five consecutive days. Cognitive tests' re-test correlations averaged at .72; for affect, test re-test correlations averaged .53. The within-person variability in cognitive tests was overall smaller (13.5% for both working memory and short-term memory, and 16% for processing speed) than in affect (24% for positive and 51.7% for negative affect). A series of linear mixed effects models showed that day-to-day-variability in cognitive function was not coupled with contemporaneous fluctuations in positive and negative affect (i.e. states; ns in all cases). Thus, affect and cognitive function fluctuate within individuals across days but they appear to do so independently of one another.

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The significance of differences in cognitive ability that occur *between* people is well documented but less is known about ability differences that occur *within* a person across repeated assessment occasions. Within-person differences exist over and above measurement error, and they confound observations of individual or between-person differences (Molenaar, 2004; Rabbitt, Osman, Moore, & Stollery, 2001; Salthouse & Berish, 2005). Also, the patterns of association for between-person differences in two or more psychological variables are distinct from the relationships that psychological processes share within a person (Borsboom, Mellenbergh, & van Heerden, 2003). For example, within-person differences in motivation and working memory differ reliably across individuals (Brose, Schmiedek, Lövdén, Molenaar, & Lindenberger, 2010), suggesting that the structure of between-person variances does not reflect the one of within-person variances. Because psychological processes occur mainly within and not between people, within-person differences are pivotal for understanding the dynamics of behavior, cognition and affect (Molenaar, 2004). In this context, the co-occurrence of changes in affect states and cognitive function is of particular interest, because it is accompanied by extensive anecdotal evidence (i.e. I felt poorly, and so I did poorly) but yet inconclusive empirical evidence.

1. Coupling effects between cognitive function and mood

According to the dual-task perspective (e.g. Ellis & Ashbrook, 1988), cognitive resources are limited and can either be allocated to performing a given task or to affective experiences and other task-unrelated cognitive processes (Goschke & Bolte, 2014). Supporting this model, emotion regulation, especially of negative emotions, has been shown to be cognitively costly (Mitchell & Phillips, 2007; Riediger, Wrzus, Schmiedek, Wagner, & Lindenberger, 2011) and linked with reduced cognitive function (Ellis & Ashbrook, 1988; Joormann, 2008).

Most previous research in this area employed experimental study designs but to test coupling effects between changes in affect and cognitive function, micro-longitudinal studies are most appropriate. Micro-longitudinal studies observe samples repeatedly over time in short intervals (e.g. hours or days) to avoid confounding by other variables that may inform cognitive changes (e.g. aging processes). Five previous articles reported data from four independent micro-longitudinal studies that tested for coupling effects between changes in affect and cognitive function (Table 1; Brose, Schmiedek, Lövdén, & Lindenberger, 2012; Brose, Lövdén, & Schmiedek, 2014; Riediger et al., 2011; Salthouse & Berish, 2005; Sliwinski, Smyth, Hofer, & Stawski, 2006). Two of the studies were lab-based, and two employed experience-sampling methods (i.e. assessment 'on-the-go'). Studies' durations spanned between 5 and 197 days with the assessment frequency ranging from once every two days to six times per day. For cognitive measures, three studies included working memory tests and one assessed a wide range of cognitive abilities. All studies included measures of affect, which refers to the experience of feeling or emotion and describes a person's mood (Watson, Clark, & Tellegen, 1988); two also assessed other state variables (i.e. motivation and attention control).

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Table 1
Overview of studies investigating coupling effects in day-to-day variability in cognitive function and affect.

Authors	Method	Assessment frequency	Cognitive measures	State measures	N	Age range
Salthouse & Berish, 2005	Palm pilot devices; correlations	6 assessments over course of 5 days	Vocabulary, processing speed, memory, executive function, reasoning & spatial visualization	Mood (single item)	271	18–89
Sliwinski et al., 2006	Lab based; mixed model approach	6 assessments over course of 8 to 14 days	Working memory (n-back, n-count, string comparison)	Negative affect (PANAS), daily stressors	108 / 68	66–95 / 18–24
Riediger et al., 2011	Mobile phones; mixed model approach	54 assessments over course of 9 days	Working memory (numerical memory-updating task)	Negative and positive affect (3 items each)	378	14–86
Brose et al., 2012	Lab based; mixed model approach	100 assessments within 197 days (average of sample)	Working memory (3-back task)	Negative affect (PANAS), motivation, attention control	101	20–31
Brose et al., 2014	Lab based; mixed model approach	100 assessments within 197 days (average of sample)	Working memory (3-back task)	Positive affect (PANAS), motivation	101	20–31

Note. Brose et al. (2012) and Brose et al. (2014) reported data from the same sample. PANAS refers to the Positive and Negative Affect Scale by Watson et al. (1988).

Coupling effects were observed in two samples. First, Brose et al. (2012) found that spatial working memory performance was lower on days of increased negative affect and reduced motivation and attention control.[1] In the same sample, they later (2014) also reported that that spatial and verbal working memory performance was improved on days with greater positive affect but they found no coupling effect for positive affect and numerical working memory. Second, Riediger et al. (2011) reported significant coupling effects for variability in numerical working memory with fluctuations in both positive and negative affect. In the remaining two samples, no such effects were detected. That said, Sliwinski et al. (2006) found a significant relationship between day-to-day variability in stress and cognitive task performance. Because the inconsistency in findings cannot be directly attributed to the studies' differences in methods, measures and samples (Table 1), we can conclude that previous research on coupling effects between day-to-day variability in mood and cognitive function is to date inconclusive.

2. The current study

The current study adds to understanding the dynamics of within-person differences in cognitive function in two significant ways. First, participants were assessed on three different cognitive abilities on five consecutive days, including measures of short-term memory, processing speed and working memory. Each day, participants completed the same tests but worked on different items. This test battery allows for one studying if changes in affect are associated with changes in specific cognitive abilities or across cognitive functions. For the other, the inclusion of a working memory test enables a direct comparison between the current findings and previous results in this area (Table 1).

Second, participants in the current study also completed daily assessments of affect, using the full Positive and Negative Affect Scale (PANAS), which differentiates positive and negative affect that are orthogonal dimensions (Watson et al., 1988). Positive affect refers to experiencing pleasure when engaging with the environment, with enthusiasm and alertness indicating high positive affect, and lethargy and sadness marking low positive affect (Watson et al., 1988). Conversely, high negative affect is characterized by the experience of subjective distress, discontent and hostility, with low negative affect reflecting the absence of such feelings (Watson et al., 1988). Some of the previous studies in this area used only short affect measures (e.g. Riediger et al., 2011) that have reduced reliability, or positive and negative affect were not jointly examined with regards to coupling effects for cognitive function (Brose et al., 2012, 2014).

3. Methods

3.1. Sample

Overall 98 participants contributed to this study, the majority of whom identified as full-time university students (N = 88) and female (N = 74). Age ranged from 18 to 75 years (mean = 23.81; SD = 8.40), with 88% of the participants aged 18 to 30 years. More than half of the sample (N = 62) listed English as their native language.

All 98 participants completed the study days 1 and 2, with one participant completing 80% of the tests on day 1 before a technical default terminated the session early. 93 participants returned on day 3; 91 returned on day 4, including 4 participants who were excluded from the analyses because they were accidentally administered the same testing materials as on the previous day; and 88 attended the final test session on day 5 (N after listwise omission = 77).[2]

3.2. Measures

3.2.1. Cognitive function battery. A cognitive test battery was developed specifically for this study that assessed short-term memory, processing speed, and working memory, respectively (Fig. 1). Tests were designed with reference to the measures from the ETS testing kit by Ekstrom, French, Harman, and Dermen (1976) and adapted for computerized administration. Test items were designed to maximize their comparability across assessment occasions (i.e. difficulty and discrimination) without administering the same item more than once. For each test, psychometric properties based on this study's sample are reported in the Results section of this manuscript

Short-term memory test. Overall 18 individual sets that consisted of 5 or 7 pairs, triplets, or quartets of combinations of letters and numbers were shown for exposure times of at least 7 s and at most 15 s. Participants were asked to recall each set's items in the order that they had been shown in within 25 s to 30 s. Sets increased in difficulty, starting with 5 pairs of letters only, and ending with 7 quartets of mixed letters and numbers. Correctly recalled pairs, triplets or quartets were coded as 1; incorrect or missed answers were coded as 0 (see also Fig. 1a). The test included overall 108 dichotomous items.

Processing speed test. Participants were shown pairs of strings that consisted of 13 numbers or combinations of letters and numbers. The strings were either identical or differed in one letter or number in any position along the string. Two blocks of 20 pairs of strings were shown (i.e. 40 items in total), each timed at 30 s. Participants had to mark if two strings were identical or not as fast as possible; correctly marked pairs were coded as 1 and all others as 0 (see also Fig. 1b).

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[1] Brose and colleagues did not mention verbal and numerical working tasks and scores in their 2012 paper.

[2] The data reported in this study are freely available on http://www.hungrymindlab.com/publications/data.

a) Short-term memory test

| 10 |
| 67 |
| 89 |
| 45 |
| 11 |

→

7 to 15 seconds   25 to 30 seconds

b) Processing speed test

```
1e3024an96sc__s / d__1e3024an96sc
5s0nk6rs4cb49__s / d__5s0vk6rs4cb49
7ln8d263by45e__s / d__7ln8p263by45e
1250935628167__s / d__1250935628967
                 ...
```

30 seconds for 20 pairs (s = same; d = different)

c) Working memory test

| 3 |
| 5 |
| 2 |
| 6 |

→

| + 3 |
| - 1 |
| - 6 |
| + 9 |

→

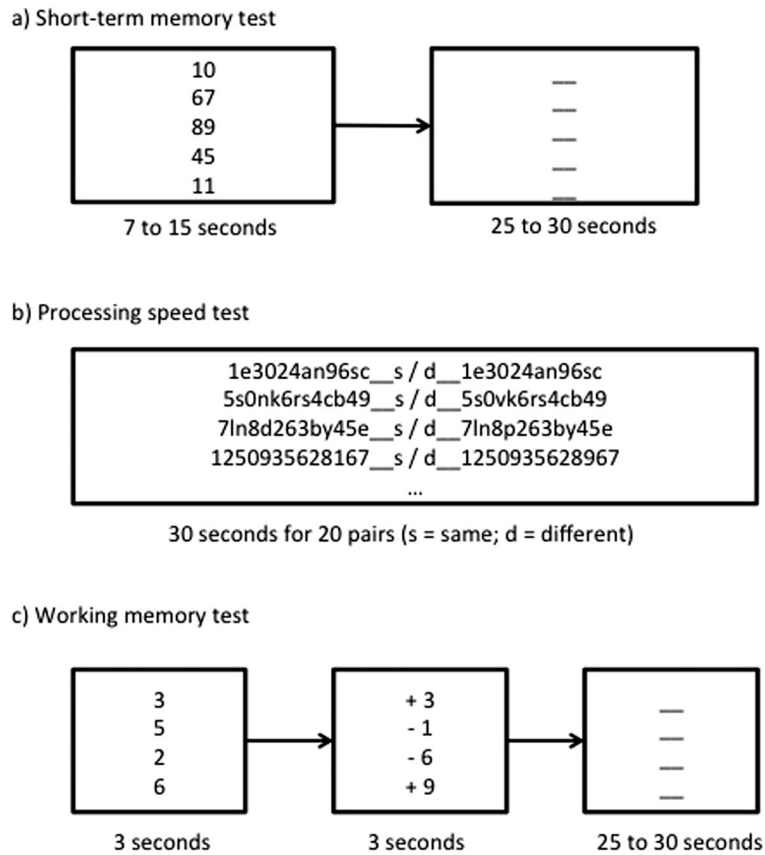3 seconds   3 seconds   25 to 30 seconds

Fig. 1. a-c Test designs for short-term memory, processing speed and working memory. Note. Exposure times are stated underneath schematic illustrations of the tests' stimuli.

Working memory test. Rows of 2, 3 or 4 single-digit numbers were shown for exposure times of 3 s to 5 s and then replaced by a second row corresponding numbers with numerical operators for the same exposure time as before. Participants were asked to enter the sums of both rows in the order that the numbers had been shown in within 25 s to 30 s. The test included increased in difficulty, with the first 2 items requiring to compute 2 sums, the next 3 items to do 3 sums, and the final 3 items to compute 4 sums. Each correctly entered sum was coded as 1; all others were coded as 0 (see also Fig. 1c). This measure consisted of a total of 29 dichotomous items.

3.2.2 Positive and Negative Affect Scale (PANAS; Watson et al., 1988). This measure consisted of 20 emotion adjectives (i.e. 10 for positive and 10 for negative affect). Participants used a slider scale ranging from 0 to 100 to indicate the extent to which they experienced each of the emotions at the moment. The slider's anchors at the extreme ends were 'Not at all' and 'Extremely' with 'Moderately' marking the score of 50. Participants had no time restrictions in completing this measure.

3.3. Procedure

Testing took place in designated research cubicles at two large universities in London, UK. On five consecutive days (i.e. Monday through Friday), participants were received by research assistants and sat in a cubicle equipped with a computer, after leaving all personal belongings outside the cubicle to minimize distractions during testing. Participants were free to arrive any time between 9 am and 6 pm. On each study day, participants completed a battery of online psychometric tests, starting with measures of affect, followed by the cognitive tests. The first session lasted on average 1 h, while all consecutive sessions lasted approximately 30 min. For affect, the same items were used every day (PANAS), while the items of the three cognitive tests differed each day and were never repeated. Participants were compensated for their efforts with course credits or online shopping vouchers.

3.4. Statistical analysis

Unit-weighted composite scores were computed for short-term memory, working memory and processing speed. Test re-test reliabilities (i.e. correlation across days) and internal consistencies were computed, before examining data plots and graphs, as well as intra-class correlations (ICC; details in Results below). Participants' average mood and cognitive function (i.e. iM) were computed by adding each day's scores per scale and dividing by the five study days. The variability in affect and cognitive function was computed as each person's Standard Deviation (i.e. iSD$_M$) from the respective iM, in addition to the Standard Deviation in each person's variability (i.e. iSD$_{SD}$). Next, linear mixed effects analysis was applied to model the relationship between cognitive function and affect across days using the lme4 package in R (Bates, Maechler, & Bolker, 2012; R Core Team, 2012; syntax in S1). Fixed effects were specified for a linear time trend (i.e. training gains) and for a linear effect of affect (i.e. independent of day-to-day variability) on cognitive function. Random effects were specified for participants' affect that deviated from the population and that were not associated with day-to-day variability (i.e. random error). Random effects were also specified for those within-person differences in affect that occurred across days (i.e. reliable day-to-day variability in affect). To test for the explanatory power of fixed and random effects, model fits are compared in linear mixed effects analyses across baseline (i.e. without the effect of interest) and specified models (i.e. including the effect of interest). Here, a first series of models tested for the role of the fixed effect of affect on cognitive function (i.e. general population effect for affect), and a second series of models tested for the random effect of affect (i.e. effect of daily

Table 2
Descriptives for affect and personality measures (i.e. individual differences).

	N	Min	Max	Mean	SD	Skew	Kurt	α
Positive affect day 1	98	2.50	90	46.41	18.28	−0.10	−0.34	.92
Positive affect day 2	98	0.10	90	40.85	20.15	0.17	−0.30	.93
Positive affect day 3	93	4.50	90	39.51	19.31	0.40	−0.12	.93
Positive affect day 4	87	2.80	88.20	37.55	19.47	0.51	−0.07	.93
Positive affect day 5	88	4.10	100	39.75	21.09	0.48	−0.10	.94
Negative affect day 1	98	0	59	13.92	12.55	1.28	1.41	.86
Negative affect day 2	98	0	50.50	11.83	10.67	1.58	2.79	.82
Negative affect day 3	93	0	56.20	10.47	12.17	1.94	3.86	.90
Negative affect day 4	87	0	72.90	10.97	12.85	2.50	8.08	.90
Negative affect day 5	88	0	54	9.82	11.42	1.77	3.18	.90
Short-term memory day 1	98	5	59	28.55	9.05	0.05	0.80	.83
Short-term memory day 2	98	7	58	32.09	8.65	−0.17	0.51	.80
Short-term memory day 3	93	8	64	34.16	8.97	−0.10	1.26	.82
Short-term memory day 4	87	2	66	33.37	9.62	0.01	1.50	.85
Short-term memory day 5	88	10	65	36.02	9.44	0.05	0.84	.84
Working memory day 1	98	0	29	16.57	7.63	−0.58	−0.24	.93
Working memory day 2	98	0	29	18.85	6.70	−0.58	−0.20	.90
Working memory day 3	93	0	29	19.91	6.19	−0.73	0.35	.89
Working memory day 4	87	0	29	20.00	6.30	−0.73	0.02	.89
Working memory day 5	88	0	29	20.78	6.27	−0.96	0.89	.90
Processing speed day 1	98	4	20	9.70	2.99	0.61	0.77	.68
Processing speed day 2	98	3	20	10.68	3.15	0.48	0.30	.64
Processing speed day 3	93	4	23	10.76	3.47	1.15	2.13	.69
Processing speed day 4	87	5	24	12.26	4.25	0.95	1.01	.79
Processing speed day 5	88	2	26	11.73	4.17	0.81	1.83	.75

Note. α refers to the internal consistency value based on the KR-20 Kuder-Richardson coefficient for dichotomous items (i.e. 1 correct, 0 missing and false).

variability in affect on cognitive function). Thus, the latter is the analysis of primary interest here because it tests if meaningful coupling effects are present. Models were fitted separately for negative and positive affect and for each cognitive test (i.e. 2 x affect and 3 x cognitive tests, resulting in 6 models per effect). The significance of model fit differences was evaluated after correcting the p-value for the number of models (i.e. 0.05/6 = .008).

4. Results

4.1. Descriptive statistics

Table 2 shows the descriptive statistics for affect and cognitive function across the five study days (i.e. inter-individual differences). All variables showed good internal consistency values, and they were by and large normally distributed, with the exception of negative affect in line with the previous literature (e.g. Brose et al., 2012). A series of

Table 4
Inter- and intra-individual differences in affect and cognitive function.

	iM	iSD	iSD_M	iSD_{SD}
Working memory	19.44	6.14	2.62	1.71
Short-term	33.73	7.58	4.56	2.10
Processing speed	11.15	3.06	1.78	1.04
Positive affect	41.00	15.8	10.0	6.10
Negative affect	11.60	9.30	6.00	5.20

Note. iM is participants' average performance across days; iSD is the sample's SD in mean performance; iSD_M is mean intra-individual difference in test scores across days (i.e. day-to-day variability within a participant); and iSD_{SD} is SD of iSD_M (i.e. average SD in intra-individual differences in cognitive test performance).

ANOVAs showed no significant differences in the study variables' means and variances for (a) participants who attended all versus fewer testing sessions, and (b) men versus women.

Cognitive test scores were positively inter-correlated across days (Table 3): correlations across short-term memory scores ranged from .49 to .83 and averaged .67; correlations for working memory ranged from .68 to .86, averaging .80; and correlations for processing speed correlated from .53 to .84, averaging .70. These values suggest high test re-test reliability for each of the cognitive tests.

By comparison, correlations for positive across days ranged from .53 to .69, averaging .59, while correlations for negative affect across days ranged from .27 to .61 with an average of .47. These results suggest that between-person differences in affect were less consistent than those in cognitive function across days. This is in line with the observation that cognitive function is relatively more stable than mood (Brose et al., 2012). Correlations between positive and negative affect ranged from r = −.13 to r = .01 across days; they were therefore largely independent of each other.

4.2. Day-to-day variability in cognitive function and affect

Fig. 2 shows a) substantial intra- and inter-individual variance for each cognitive test in performance across study days, b) small average score gains or training effects for each cognitive test over time, and c) ceiling effects for working memory. Fig. 3 summarizes the ICC for cognitive function and affect, confirming that for all study variables the majority of variance occurred between rather than within individuals. That said, the ICC also confirmed that within-person differences accounted on average for twice as much of the variance in positive and negative affect compared to the cognitive tests.

Table 4 summarizes the mean of participants' individual average score in study variables across days (i.e. iM), the average Standard Deviation of participants in each variable across days (i.e. intra-individual variability; iSD_M), and the extent to which participants differed in this
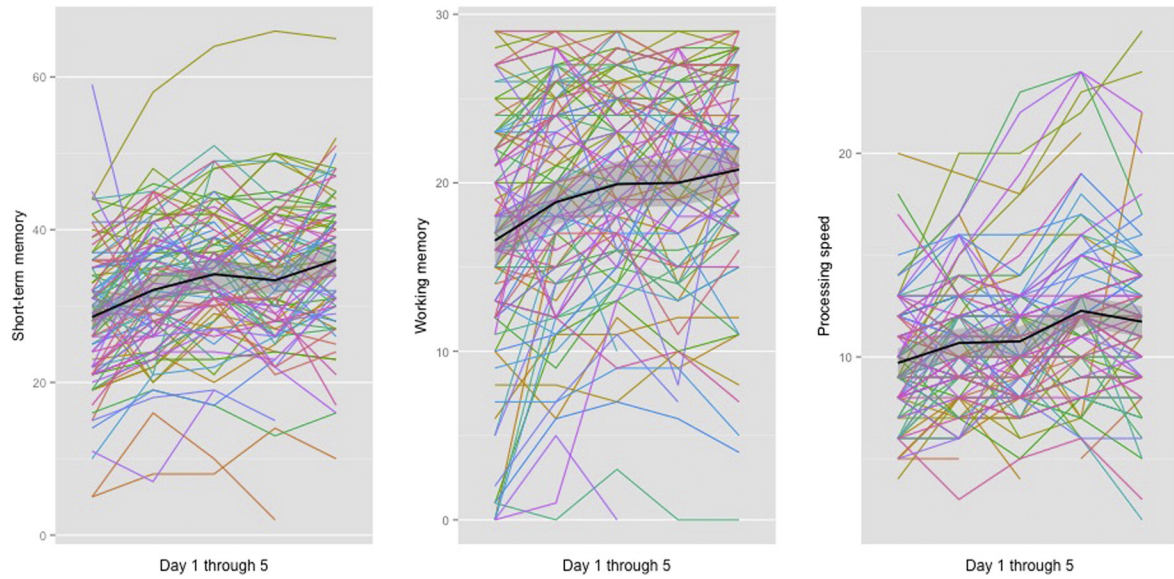
Table 3
Correlations for cognitive test scores across five study days.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Working memory day 1**	-													
2	**Working memory day 2**	.80	-												
3	**Working memory day 3**	.77	.86	-											
4	**Working memory day 4**	.74	.80	.83	-										
5	**Working memory day 5**	.68	.81	.87	.82	-									
6	**Short-term memory day 1**	.27	.34	.36	.25	.33	-								
7	**Short-term memory day 2**	.45	.45	.46	.43	.38	.66	-							
8	**Short-term memory day 3**	.42	.43	.42	.46	.38	.67	.80	-						
9	**Short-term memory day 4**	.42	.42	.44	.44	.42	.56	.76	.83	-					
10	**Short-term memory day 5**	.38	.47	.50	.47	.50	.49	.68	.65	.78	-				
11	**Processing speed day 1**	.41	.30	.28	.24	.15	.01	.22	.11	.10	.15	-			
12	**Processing speed day 2**	.42	.29	.28	.27	.13	.06	.24	.13	.09	.06	.69	-		
13	**Processing speed day 3**	.21	.15	.19	.15	.00	.00	.18	.07	−.01	.03	.54	.73	-	
14	**Processing speed day 4**	.27	.14	.17	.22	.02	.04	.20	.10	.02	.04	.57	.73	.83	-
15	**Processing speed day 5**	.25	.10	.16	.12	.01	.04	.14	.03	.08	.10	.53	.78	.77	.77

Note. N = 77 after listwise omission.

Fig. 2. Spaghetti plots of performance of all participants across five study days in cognitive abilities. Note. Each participant's performance scores are represented by a colored line. The black line marks the sample's mean trend in performance across days.

Standard Deviation (i.e. inter-individual differences in variability; $i\text{SD}_{\text{SD}}$). Overall, intra-individual variability in affect were greater than in cognitive function, confirming the relative within-person stability of cognitive function by comparison with affect.

4.3. Coupling effects between affect and cognitive function

Models including fixed effect terms for negative affect failed to provide a significantly better fit compared to models without fixed effect terms for negative affect (p > .05, in all cases). Similarly, models including random effects for negative affect – that is, for day-to-day variability in affect – did not differ significantly in fit from models excluding such terms (p > .05, in all cases). Thus, negative affect was here not associated with cognitive function. For random effects of positive affect, similar results were observed: models specifying effects of day-to-day variability in positive affect on cognitive performance did not fit notably better than models without random effects for positive affect (p > .05 in all cases). However for the fixed effects of positive affect, one significant association was observed: positive affect was

associated with improved processing speed across days ($X^2_{\text{diff}} = 7.2$, df = 1, p = 0.007) but not with working and short-term memory.

In summary, no coupling effect was observed between daily changes in affect and cognitive function, although both were subject to substantial inter- and intra-individual differences. The only association that was found to be statistically significant suggested that higher positive affect was linked to improved processing speed.

5. Discussion

Within-person differences in intelligence are important to understand because they confound between-person differences, inform psychological processes, and are implied in cognitive development (Molenaar, 2004; Salthouse & Berish, 2005). The current study tested if within-person differences in affect are coupled with within-person differences in cognitive function across days.

Considerable day-to-day variability in affect and cognitive function were observed, but no correspondence or coupling effect was detected between the two. This finding is in line with the results of some previous
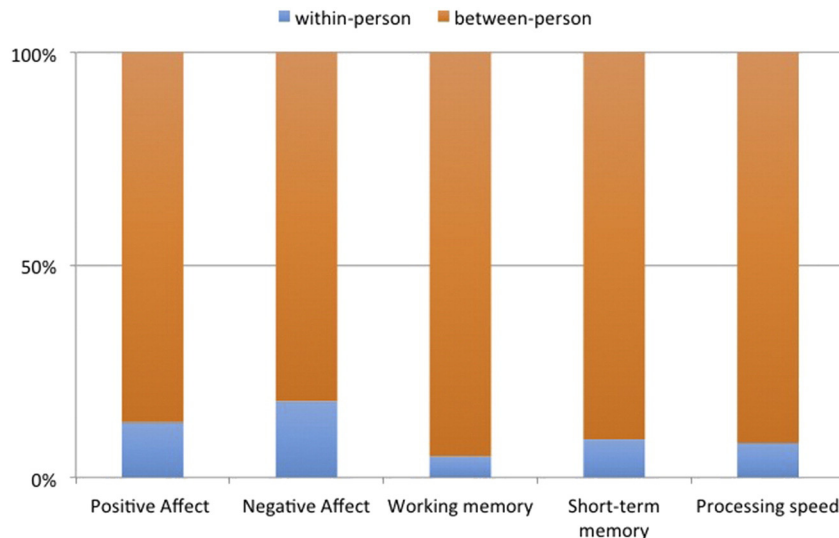

Fig. 3. Bar plot of intra-class correlations in affect and cognition. Note. Intra-class correlations differentiate variance that occurs within and variance that occurs between people.

studies but it contradicts others (Table 1). Furthermore, this study's failure to identify a relationship between changes in negative affect, referring to the experience of distress, discontent and hostility, and changes in cognitive function is at odds with the dual-process model that suggests that emotional experiences are cognitively costly and thus, impair cognitive performance (Brose et al., 2012; Ellis & Ashbrook, 1988; Goschke & Bolte, 2014). It is, however, possible that normal day-to-day fluctuations in negative affect are not extreme enough to place notable demands on a person's cognitive resources. In other words, dramatic changes in negative affect or clinically low levels of mood may well reduce cognitive function across days (Joormann, 2008) but these did not occur in the current study. Similar to the findings for negative affect, day-to-day variability in positive affect was unrelated to daily changes in cognitive abilities. That said, higher positive affect was associated with better processing speed, and this association was independent of day-to-day changes in affect and cognitive function. Previous experimental studies also reported benefits of positive affect for processing speed (e.g. Stanley & Isaacowitz, 2011) but the current study is the first to provide (micro)longitudinal evidence. Put bluntly, the result suggests that people who have a general tendency to be more enthusiastic and alert have faster brains but additional research will be needed to substantiate this observation. That said, this finding supports in general the idea that patterns of association for between-person differences are distinct from relationships among within-person differences (Borsboom et al., 2003; Brose et al., 2010), because inter-individual differences in positive affect were associated with variability in cognitive function while intra-individual differences in positive affect were not.

5.1. Strengths and limitations

This study has several strengths, including repeated assessments in regular intervals of three different cognitive abilities using psychometric tests, whose scores are comparable across measurement occasions. It is also not without weaknesses. First, the current study's sample size was relatively small to study coupling effects between two or more variables across time, although the sample was of sufficient size for the reported analyses (Bates et al., 2012) and similar to previous studies (e.g. Brose et al., 2012, 2014). Second, the current study spanned only a short time period (i.e. fives days) with relatively large time intervals (i.e. days). Although similar study duration and assessment intervals have been previously applied (Table 1), it is possible that coupling effects only become detectable if affect and cognitive function are observed across long periods and at short time intervals (e.g. hours). Finally, the current study was lab-based, and this setting is likely to reduce the reliability and variability in affect scores compared to using experience-sampling methods that allow assessing affect 'on-the-go' and independent of lab-related influences.

5.2. Conclusions

Differences in cognitive function that occur within people across assessment occasions are thought to be at least partially attributable to the person's changes in affective states, but the empirical evidence for such coupling effects is inconsistent to date. The current study failed to detect a meaningful association between day-to-day within-person variability in cognitive function and affect, although there was some evidence for inter-individual differences in positive affect to be associated with in inter-individual differences processing speed. The findings suggest that changes in affect do not translate into contemporaneous changes in cognitive function.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.intell.2015.12.006.

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