Lifespan Transformations in the Couplings between Intellectual Abilities and Constituent Cognitive Processes

Shu-Chen Li*, Ulman Lindenberger*, Bernhard Hommel†, Gisa Aschersleben†, Wolfgang Prinz†, Paul B. Baltes*

*Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin
† Max Planck Institute for Psychological Research, Munich

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Address correspondence to: Shu-Chen Li
Center for Lifespan Psychology
Max Planck Institute for Human Development
D-14195 Lentzeallee 94, Berlin
GERMANY
Tel.: +(49) 30 82406 305
Fax: +(49) 30 82499 39
Email: shuchen@mpib-berlin.mpg.de
Abstract

Two-component theories of lifespan cognition postulate that biology-based fluid abilities develop and decline earlier during child development and aging, respectively; and they, in turn, support or constrain the acquisition and expression of knowledge-based crystallized abilities. Thus, maturation and senescence compress the space of intellectual functioning by imposing age-specific constraints upon its constituent processes. Hence, the couplings among different intellectual abilities and cognitive processes are expected to be strong in childhood and old age. Findings from a population-based study of 291 individuals aged 6 to 89 years support these predictions. Furthermore, processing robustness, a frequently overlooked processing aspect, predicted fluid intelligence beyond processing speed in old age but not in childhood, suggesting that the causes of more compressed intellectual space differ between maturation and senescence. Research on developmental changes in functional brain circuitry may profit from explicitly recognizing lifespan transformations in the organization of intellectual abilities and their underlying cognitive processes.
Spearman (1904) discovered the ubiquitous positive intercorrelations among intelligence tests. Since then, over a century of intelligence research has predominantly viewed the structure of intelligence as static (see Carroll, 1993; Reinert, 1970; Sternberg, 1994 for overviews), overlooking possible developmental transformations in the organization of intellectual abilities and their underlying information-processing and neurobiological mechanisms.

A Dynamic View of Lifespan Intellectual Development

Two-component theories of intellectual development (e.g., Baltes, Lindenberger & Staudinger, 1998; Cattell, 1971; Horn, 1968, 1970) suggest an alternative to a static ability structure, by considering the functional organization of intellectual abilities as dynamic—developing and transforming throughout life. Finding stronger correlations between subtests of intelligence in children than in adolescents, early developmentalists (e.g., Garrett, 1946) suggested the gradual differentiation of a general ability into fairly distinct aptitudes during maturation. This notion was later extended to cover the lifespan. Specifically, the differentiation-dedifferentiation hypothesis (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980) postulated that intellectual abilities are rather undifferentiated in childhood, undergo differentiation during maturation leading to a multi-faceted ability structure that remains largely invariant during adulthood, and becomes undifferentiated again (dedifferentiation) during senescence.

Three concepts are central in accounting for lifespan transformations in the organization of intellectual abilities. The first is the categorization of two related facets of intelligence along the continuum from more biology-based fluid abilities to more knowledge-based crystallized abilities (Cattell, 1971; Horn 1968, 1970). A conceptually similar distinction is that between the fluid cognitive mechanics and crystallized cognitive pragmatics\(^1\) (Baltes, Lindenberger, & Staudinger, 1998). The second is the concept that neurobiological and cultural, experiential influences interact with each other to jointly bring forth intellectual development throughout life. The relative contributions of biology and
culture are assumed to vary across life periods and ability domains (e.g., Baltes, 1987; Baltes et al., 1998; Li, 2003; Lindenberger, 2001). The third is the proposition that during life periods when there are strong biological constraints on information-processing mechanisms underlying knowledge acquisition and expression, greater strengths of coupling between different facets of intelligence and their constituent processes are expected. Specifically, when brain maturity is reached and cognitive processes implementing fluid abilities function at (or above) threshold levels, any subsequent development in knowledge-based crystallized abilities is primarily conditioned by contextualized personal experiences, such as educational background and occupational expertise. In contrast, during maturation and senescence the neurobiological substrates of intellectual functioning apparently grow and decline, respectively; and they play crucial roles in the development and aging of information-processing mechanisms underlying fluid abilities. During maturation, on the one hand, increments in fluid abilities support knowledge acquisition (e.g., Cattell, 1971; Horn, 1968), and during aging, on the other hand, declines in fluid abilities limit the expression of culture-based knowledge (e.g., Baltes et al., 1998). Hence, it can be expected that fluid and crystallized intelligence, together with their constituent cognitive processes, are more strongly related with each other at both ends of the lifespan.

**Aims of the Present Study**

In light of recent evidence showing lifespan differences in: (1) functional cortical organization during childhood development (see Johnson, 2001 for review) and aging (see Cabeza, 2002; Reuter-Lorenz, 2002 for reviews) and; (2) genetic contributions to intelligence (see Plomin & Spinath, 2002 for review), behavioral research on lifespan transformations in the organization of intellectual abilities reaches another level of relevance. Parallels between lifespan transformations of cognitive functioning both at the neurobiological and the behavioral levels need to be identified to facilitate integration of corresponding phenomena across levels (e.g., Li, Lindenberger, & Sikström, 2001).
Although findings supporting the distinction between fluid and crystallized intelligence and their differential lifespan trajectories have accumulated (see Horn 1970; Horn & Noll, 1997 for reviews), the differentiation-dedifferentiation phenomenon per se has rarely been investigated directly. Examining lifespan transformations requires a broader spectrum of tasks and a broader age span than has been previously covered. So far, most studies examined childhood (e.g., Garrett, 1946) or old age (e.g., Baltes et al., 1980; Schaie, Maitland, Willis, & Intrieri, 1998) separately. In the rare cases when a limited age range covering both childhood development and aging was included, either age-adjusted tests precluding developmental comparative analyses or discontinuous age groups were used (e.g., Balinsky, 1941). The research has also rarely combined a dynamic differentiation-dedifferentiation view of lifespan intellectual development with inquiries about information-processing correlates of intelligence, albeit integration of psychometric and experimental approaches has been pursued in research on adult cognition and aging (see Craik & Salthouse, 2000; Deary, 2001 for review). Furthermore, although performance fluctuation has been considered in developmental and aging research (e.g., Horn, 1968; Welford, 1981), studies on information-processing correlates of intelligence have predominantly focused on processing speed. However, processing robustness (i.e., less performance fluctuation) is also of interest, because speed and accuracy aside, intraindividual response fluctuations when carrying out a given task across multiple trials reflect another aspect of information processing. Recent findings suggest that decreased processing robustness may reflect attenuated brain integrity due to pathology or aging (e.g., Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000; Li, Aggen, Nesselroade, & Baltes, 2001; Rabbitt, Osman, Moore, & Stollery, 2001). The majority of existing studies on information-processing mechanisms of intelligence have neglected this aspect, so there are no data on lifespan differences in processing robustness and its relations to intellectual abilities.

The present research aims at addressing some of these limitations. Fifteen psychometric tests measuring fluid and crystallized abilities and ten basic experimental
cognitive tasks measuring processing speed and robustness were administered to a population-based lifespan sample covering a wide age range. Specifically, we directly focused on lifespan differences in the strength of coupling (covariation) between different intellectual abilities and the speed and robustness of their underlying information-processing mechanisms.

**METHODS**

*Sample*

A lifespan sample with 356 participants aged 6 to 89 years was randomly drawn from a parent sample of 1920 individuals whose names and addresses were provided by the Berlin City Registry. The study sample was stratified by age and sex. In view of differential rates of developmental changes across the lifespan, from age 6 to 15, 16 to 59, and 60 to 89, 1-year, 4-year, and 3-year age bins were used for the age stratification, respectively. Excluding participants who missed multiple testing sessions, had severe health impairments, or whose data contributed to multivariate non-normality, the working sample consisted of 291 participants (149 males and 142 females) uniformly distributed across 31 age bins. Excluded participants were distributed almost evenly across life periods (13 children, 21 adolescents, 18 adults, and 13 old adults). To examine lifespan differences in the couplings between intellectual abilities and cognitive processes, the sample was divided into continuous age groups covering six life periods: childhood (6-11 years), adolescence (12-17 years), early adulthood (18-35 years), middle adulthood (36-54 years), late adulthood (55-69 years), and old age (70-89 years).

*Psychometric Measures*

A battery of 15 psychometric tests from the Berlin Aging Study were administered to all participants. The factor structure of these tests reflecting five primary intellectual abilities, which, in turn, define fluid and crystallized intelligence at a higher level of
aggregation, was documented previously (see Lindenberger & Baltes, 1997). The five ability factors included: (1) Mental Mapping (commonly known as Perceptual Speed in the psychometric tradition), measured by the accuracy of Digit-Letter Substitution, Digit-Symbol Substitution, and Identical Picture tests; (2) Memory, measured by Activity, Paired Associate, and Text Recalls; (3) Reasoning, measured by tests of Figural Analogies, Letter Series, and Practical Problems; (4) Verbal Knowledge, measured by tests of Practical Knowledge, the Spot-a-Word and Vocabulary tests; (5) Verbal Fluency, measured by tests of naming names of animals, red things, and words beginning with S. The first three abilities were indicators of fluid intelligence (gf) and the last two defined crystallized intelligence (gc). The fluency tests have sometimes been viewed as hybrid measures of fluid and crystallized intelligence (e.g., Lindenberger & Baltes, 1997; Salthouse, 1993), as they may, in part, reflect processing aspects of intellectual functioning (e.g., working memory and processing speed) as well as verbal knowledge.

**Experimental Cognitive Tasks**

Speed indices (e.g., reaction times) are common information-processing correlates of intelligence. Individual differences in information-processing speed and other aspects of cognition have been documented separately in the childhood development (e.g., Fry & Hale, 1996) or aging (see Craik & Salthouse, 2000 for review) literature. By piecing together results from developmental and aging studies, processing speed has been conceptualized as an information-processing resource underlying intellectual development across the lifespan (e.g., Cerella & Hale, 1994; Kail & Salthouse, 1994). For the present study, we adapted five pairs of basic experimental cognitive tasks (BECTs) to assess the speed and robustness of a range of processes, including visual search, response competition, memory search, and choice reactions.

The stimuli used in the visual search task were filled and unfilled squares and circles. In feature search, the participants searched for a filled circle (target) among empty circles (distractors). In conjunction search, the participants searched for the target from a
background of distractors comprising both filled squares and empty circles. A modified version of the Flanker task with two response conditions was used. In the compatible condition, the color of the distractors was the same as the target, whereas in the incompatible condition the color of the distractors not only differed from the target, but was identical to an alternative competing response. Memory search was measured by two tasks. The first was a task involving matching the names of letters. The participants were presented with pairs of uppercase, lowercase, and mixed-case letters (from the set A, a, B, b). In the physical identity condition, the participants responded whether the letters were physically identical (e.g., AA and bb). In the name-matching condition, the participants had to search semantic memory for the “names” of corresponding letters in order to respond whether the letters shared identical names (e.g., Aa and Bb). A second memory task was the memory condition of a pattern-matching task. The stimuli were pairs of circles, each circle having three dots on its circumference. The participants responded whether the spatial patterns of the dots in a given pair of circles were the same. In the matching condition, a stimulus pair was presented side by side, hence no memory process was required; whereas in the memory condition, the two items in a given pair were presented with a 3000 ms delay between them. Simple and choice reactions were also assessed.

RESULTS

Lifespan Age Gradients of Intellectual Abilities, Speed, and Robustness

The cross-sectional age gradients of all variables are summarized in Figure 1. Composite scores of the psychometric measures were transformed into T-scores (mean = 50, SD = 10). The fitted curves were based on the group means of 31 age bins and were derived from a combined exponential growth and decline function for reaction times (RT; cf. Cerella & Hale, 1994) that was modified also for accuracy, speed, and robustness data. Across all measures, the fitted curves account for substantial portions of variance ($r^2$ ranged from .73 to .97, $M = .89$). As might be expected from the hybrid nature of the fluency measures, indeed, the age gradient of verbal fluency falls in between those of fluid
abilities and verbal knowledge, but lies closer to verbal knowledge.

Given the a priori theoretical distinction and the differential age gradients of fluid and crystallized abilities in our data, separate composite scores of fluid and crystallized intelligence were computed. Besides reporting raw RT data, the RTs of each of the BECTs were transformed into processing speed by taking the inverse of RT (i.e., 1/RT), a measure which also corrects the skewness of RT distributions. For the entire sample, the correlations between RTs for the BECTs ranged from .69 to .81. A composite score of processing speed based on the standardized 1/RTs of each of the BECTs was computed and transformed into T scores. We computed an individual processing robustness score based on the composite of standard deviations of the trial RTs for all the BECTs. The composite was then reflected so that a higher score signified relatively small intraindividual trial-by-trial RT fluctuations in all the BECTs.

Keeping in mind the caveat that cross-sectional age differences are only approximations of true longitudinal growth and decline (Molenaar, Huizenga, & Nesselroade, 2003), the overall results supported the distinction and the interplay between fluid and crystallized intelligence. Age gradients of more biology-based fluid intelligence and more knowledge-based crystallized intelligence showed a lead-lag pattern, with fluid intelligence exhibiting earlier growth and decline than the development and aging of crystallized intelligence (Fig. 1A).

Reaction times of the BECTs showed various rates of growth and decline (Fig. 1B). Quite expectedly, the more difficult tasks (e.g., conjunction visual search) showed steeper growth and decline compared to the easier tasks (e.g., simple reactions). Furthermore, on the continuum from biology- to knowledge-based intellectual abilities, lifespan age gradients of processing speed and processing robustness corresponded very closely to the gradient of more biology-based fluid intelligence, but less so to more knowledge-based crystallized intelligence (Fig. 1C). Maximum performances of processing speed, processing robustness, and fluid intelligence were achieved by individuals in their mid 20s. Decrements were already visible by age 30. The maximum crystallized intelligence scores
were achieved by individuals in their mid 40s and remained stable until old age, at which point they also declined (beyond 70 years of age, $r_{age, ge} = -.45$, $p < .01$).

These results corroborate previous findings of differential age trajectories of fluid and crystallized intelligence (e.g., Horn, 1970; Jones & Conrad, 1933; McArdle, Ferrer-Caja, Hamagami, & Woodcock, 2002). Furthermore, they show clear parallels between the growth and decline of processing speed, processing robustness, and fluid intelligence. Besides measures indicating the efficiency of mental operation, fluid intelligence also manifests in accuracy-based measures of reasoning and memory abilities. The close correspondence obtained for the age-gradients of processing robustness and fluid intelligence offers evidence for the relationship between the development of intellectual functioning and processing robustness over the lifespan.

----- Insert Figure 1 about here -----

Individual differences in processing speed and robustness were highly correlated. However, results from variance component analyses showed that, in late adulthood and old age, processing robustness directly accounted for as much variance in fluid intelligence as did processing speed. This was not the case in predicting crystallized intelligence. Moreover, processing robustness predicted old people’s chronological age above and beyond processing speed (Table 1). Intriguingly, all of these effects were unique to aging.

----- Insert Table 1 about here------

*Lifespan Differences in the Correlations between Intellectual Abilities and Information Processing*

Lifespan differences in the strengths of coupling between intellectual abilities and processing speed were investigated in adjacent age groups covering six life-periods. The equivalence of between-individual variance across age groups was examined first. Tests of homogeneity (Cochran’s $C$ and Bartlett-Box $F$) showed that except for memory and processing speed derived from one BECT (i.e., pattern-matching task), homogeneity of between-individual variance obtained across the six age groups. Furthermore, the
differences in these two measures neither favored the children nor the old adults for exhibiting stronger correlations between variables. When adjacent age groups were combined to produce larger sample sizes per group, the results remained similar to those with the six age groups presented below. Reliability tests also showed that estimates of internal consistency of most psychometric and experimental measures, except activity recall, were comparable across age groups (Cronbach’s alpha ranged from .80 to .96 for RT measures, .65 to .95 for most psychometric tests except for memory tests, which ranged from .40 to .85). Excluding activity recall, which was less reliably measured in early adulthood, from the analyses did not change the results.

Overall, the extent of differentiation (i.e., multiple ability dimensions) inferable from the interrelationship of the psychometric tests was estimated by the number of dominant principal components (PC) for each age group. As predicted, the estimated number of dimensions of the correlation matrix involving the 15 tests was smaller in childhood, late adulthood, and old age (Fig. 2A) than in adolescence, young, and middle adulthood (Fig. 2B). Relatedly, the amount of variance accounted for by the first PC was larger at both ends of the lifespan, for BECTs as well as for psychometric measures (Fig. 2C).

Regarding specifically the association between the biology- and knowledge-based aspects of intelligence (Fig. 2D), we found that fluid and crystallized intelligence were more highly correlated in childhood, late adulthood, and old age than in adolescence, young, and middle adulthood (z = 3.7).

As for the coupling between these two facets of intelligence and information processing (Fig. 2E), processing speed correlated significantly with fluid intelligence across all age groups (p < .01), and these correlations were stronger in childhood and old age than in adolescence and adulthood (z = 1.9). Overall, the correlations were weaker for crystallized intelligence. Processing speed correlated more highly with fluid than with crystallized intelligence in childhood and in old age (z = 2.74 and z = 2.77, respectively). Similar trends were found in other age groups. Nevertheless, the pattern of stronger coupling with processing speed at both ends of the lifespan was similar to that observed
for fluid intelligence. In this case, significant correlations were found in childhood, late adulthood, and old age.

------- Insert Figure 2 here----------

The shared variance between processing speed and chronological age in predicting intelligence was examined more closely. The amount of predicted variance in fluid (Figure 3A) and crystallized (Fig. 3B) intelligence that was shared between processing speed and age was highest in childhood and lowest in adulthood, although the overall percentage was smaller when predicting crystallized intelligence. These results suggest that factors contributing to lifespan transformations in the organization of intellectual abilities may, in part, also contribute to their age gradients.

As a metric of physical time, chronological age by itself does not have any direct causal influence on development, albeit being an accepted proxy. The central task of developmental research is to specify endogenous and exogenous processes bearing direct functional relations with development over time, thereby explicating the role of age. In this vein, we examined how well the relatively more internal (e.g., biological influences on information-processing mechanisms) and the relatively more external (e.g., cultural influences on knowledge acquisition and expression) processes as reflected in the entire set of measures predicted individual differences in chronological age. Specifically, we compared whether the amount of shared variance indicating the coupling strength between internal biology-based and external culture-based influences was larger at both ends of the lifespan. Results from a variance component analysis, with processing speed, fluid and crystallized intelligence predicting chronological age, gave a positive answer. As shown in Fig. 3C, significant amounts of individual differences in chronological age were accounted for by these variables in childhood (68%), adolescence (28%), late adulthood (22%), and old age (26%); but not in young (9%) and middle adulthood (11%). Moreover, at both ends of the lifespan a larger percentage of the predicted variance in chronological age was jointly shared between processing speed and the two facets of intelligence, amounting to 81% and 69% of the explained variance in childhood and in old age, respectively.
DISCUSSION

Reexamining the century-old question of the structure of intellectual abilities through the lens of lifespan theories (e.g., Baltes et al., 1998; Horn, 1968; Reinert, 1970), we found that the couplings between fluid and crystallized intelligence (or termed differently, between cognitive mechanics and pragmatics) and their constituent cognitive processes were stronger at both ends of the lifespan (Fig. 2). These results indicate more compressed functional organization of intellectual abilities and cognitive processes in childhood and old age than in adulthood and support the differentiation-dedifferentiation view of intellectual development across the lifespan. Our behavioral data mirror recent cognitive neuroscience findings of dynamic cortical functional organization with increasing processing specificity during maturation (Johnson, 2002) but decreasing specificity (Logan, Sanders, Snyder, Morris, & Buckner, 2002) or increased compensatory integration during senescence (Cabeza, 2002; Reuter-Lorenz, 2002).

Furthermore, we also found evidence of closely corresponding lifespan age gradients between information-processing speed, processing robustness, and fluid intelligence (Fig. 1C). Overall, these two aspects of information processing are more closely related with fluid than with crystallized intelligence, particularly during maturation and senescence (Fig. 2E). In accordance with previous research on cognitive aging showing that fluid abilities correlated more with basic sensory processing, whereas crystallized abilities correlated more with socio-biographical predictors (Lindenberger & Baltes, 1997), our results provide further support for the neurobiology vs. acculturation distinction between these two facets of intelligence.

The lifespan conception is also helpful for discerning similarities and differences between maturation and senescence. Regarding similarities, processing speed was slower and the levels of processing robustness and intellectual abilities were lower at both ends of the lifespan. The organization of intellectual functioning was less differentiated both in the maturation and senescence portions of the lifespan. These similarities notwithstanding, our results also demonstrated that senescence is not merely the mirror reversal of maturation.
This was illustrated by the fact that processing robustness was predictive of fluid intelligence and chronological age only in late adulthood and old age, but not in childhood. This result is consistent with other recent findings suggesting that decreased processing robustness in old age might reflect attenuated brain integrity due to aging (e.g., Hultsch et al., 2000; Li et al., 2001; Rabbitt et al., 2001). Together, these results lend support to the processing noise hypothesis of cognitive aging (Welford, 1981), be it conceptualized either at the information-processing or neurobiological level, or both (Li, Lindenberger, & Sikström, 2001).

Two limitations of the present study are pertinent to lifespan theories. First, given the relatively small sample size per age group (on average n = 48), in addressing the overall relatedness between intellectual abilities and cognitive processes we limited our analyses to robust and generally accepted exploratory methods (e.g., principal components) in lieu of classical factor analysis. Relative to confirmatory approaches, these analyses yield cruder comparisons of lifespan age differences in factorial structure per se. Second, present conclusions are drawn on the assumption that age-comparative studies of interindividual differences shed light on age changes at the intraindividual level. This assumption cannot be tested with the present data set (cf. Molenaar et al., 2002, for relevant proofs and simulations). These limitations call for additional longitudinal lifespan studies with larger samples to examine the dynamics as well as the correspondences between age differences and age changes of intelligence structure in greater details (cf. Ghisletta & Lindenberger, in press; McArdle, Ferrer-Caja, & Hamagami, 2002).

In conclusion: Results of this study make a clear case for more careful considerations of lifespan transformations in both the level and covariation of intellectual abilities and their underlying cognitive processes (e.g., Baltes et al., 1998; Li et al., 2001). In a related vein, recent theories of developmental disorders also stress developmental dynamics as a key to understanding cognitive impairments (Karmiloff-Smith, 1998). Lifespan transformations along the continuum of chronological age such as were observed here serve as a window to identifying other variations in the functional organization of
intellectual abilities and neurocognitive processes that are symptomatic of developmental disorder or low ability level in general, as Spearman (1904) had initially pondered. As cognitive neuroscience rapidly advances towards mapping functional brain circuitry using as indicators cognitive tasks in conjunction with cultural, experiential influences (Hedden, Park, Nisbett, Ji, Jing, & Jiao, 2002; Johnson, 2001; Li, 2003; Paulesu et al., 2001), the behavioral phenomena of lifespan transformations in the functional organization of intellectual abilities and cognitive processes should be acknowledged and further exploited.
REFERENCES


Neuropsychology, 14, 588-598.


Footnote

In linking the Cattell-Horn (gf-gc) theory of fluid and crystallized intelligence to lifespan and cognitive psychology, Baltes (1987) distinguished between two domains of intellectual functioning with cognitive mechanics referring to information-processing mechanisms implementing the fluid abilities, and cognitive pragmatics referring to culture- and knowledge-related applications of the cognitive mechanics. The distinction between cognitive mechanics and pragmatics generalized the gf-gc theory beyond psychometric tradition to encompass theories and findings from evolutionary biology, anthropology, cognitive experimental psychology, and expertise research, among others (for further details see Baltes et al., 1998).
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Table 1. Results of variance component analysis showing the unique predictive validity of processing robustness in late adulthood and old age (56 to 89 years). The percentages of explained variance in fluid intelligence, crystallized intelligence, and chronological age that were uniquely predicted by processing speed, processing robustness, and shared between processing speed and robustness.

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Fluid Intelligence</th>
<th>Crystallized Intelligence</th>
<th>Chronological Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing Speed</td>
<td>4.1 (p &lt; .01)</td>
<td>4.4 (p &lt; .01)</td>
<td>0.6 (p &gt; .38)</td>
</tr>
<tr>
<td>Processing Robustness</td>
<td>4.7 (p &lt; .01)</td>
<td>0.1 (p &gt; .74)</td>
<td>6.5 (p &lt; .006)</td>
</tr>
<tr>
<td>Shared Speed and Robustness</td>
<td>28.7 (p &lt; .001)</td>
<td>13.3 (p &lt; .01)</td>
<td>41.9 (p &lt; .001)</td>
</tr>
<tr>
<td>Total</td>
<td>37.5 (p &lt; .001)</td>
<td>13.5 (p &lt; .01)</td>
<td>48.8 (p &lt; .001)</td>
</tr>
</tbody>
</table>


**Figure Captions**

*Figure 1.* Lifespan age gradients of intellectual abilities and cognitive processes. (A) Group means and estimated age gradients of five intellectual abilities, i.e., verbal knowledge, verbal fluency, reasoning, mental mapping, and memory. (B) Group means and estimated age gradients of reaction times for basic experimental cognitive tasks. The tasks are denoted with the following labels: Vsfea = visual feature search; VScon = visual conjunction search; Fcon = Flank task, compatible condition; Ficon = Flanker task, incompatible condition; Phys = Posner task, physical identity condition; Name = Posner task, name identity condition; Mat = pattern-matching task; Mem = memory-matching task. Sim = simple reaction-time task; Cho = choice reaction-time task. (C) Comparisons of lifespan age gradients of fluid intelligence, crystallized intelligence, processing speed, and processing robustness.

*Figure 2.* Lifespan differences in the coupling between intellectual abilities and processing speed. (A) Scree plot of principal component analysis (PCA) of intellectual abilities for groups of individuals in childhood, late adulthood, and old age. For all 3 age groups, the elbows of the scree plot and the number of dominant principal component (i.e., Eigen Value > 1) indicated that the estimated number of dimensions of the mental space spanned by the 15 tests was 2. (B) Scree plot of PCA of intellectual abilities for groups of individuals in adolescence, young adulthood, and middle adulthood. The estimated number of dimensions was 5. (C) Percentages of variance in 10 basic experimental cognitive tasks of processing speed and 15 measures of intellectual abilities accounted for by the first PC in six age groups. (D) Correlations between fluid and crystallized intelligence in six age groups. (E) Correlations between processing speed and two facets of intelligence in six age groups.
Figure 3. Results from variance component analyses showing lifespan differences in the amount of shared variances. (A) Percentages of unique processing speed, age, and shared variances in predicting fluid intelligence in six age groups. All amounts of explained variance are significant beyond the .05 level, with the exception of unique age variance and the shared variance in early and middle adulthood. (B) Percentages of unique processing speed, age, and shared variances in predicting crystallized intelligence in six age groups. Overall the amounts of predicted variance are less than that in predicting fluid intelligence. Except for late adulthood, processing speed has no unique contribution. (C) Percentages of total and shared explained variances in chronological age predicted by processing speed, fluid (gf) and crystallized (gc) intelligence.
Figure 1

A

![Graph A](image)

B

![Graph B](image)

C

![Graph C](image)
Figure 2

(A) Eigenvalues for Dimension A across different age groups (6-11 years, 12-17 years, 18-35 years, 36-55 years, 56-69 years, 70-89 years)

(B) Eigenvalues for Dimension B across different age groups (6-11 years, 12-17 years, 18-35 years, 36-55 years, 56-69 years, 70-89 years)

(C) Correlation between BICT Processing Speed and Mental Abilities across different age groups (6 to 11, 12-17, 18-35, 36-55, 56-69, 70-89)

(D) Correlation between Fluid Intelligence and Mental Abilities across different age groups (6 to 11, 12-17, 18-35, 36-55, 56-69, 70-89)

(E) Correlation between Fluid Intelligence and Crystallized Intelligence across different age groups (6 to 11, 12-17, 18-35, 36-55, 56-69, 70-89)
Figure 3