Research Article

Transformations in the Couplings Among Intellectual Abilities and Constituent Cognitive Processes Across the Life Span

Shu-Chen Li,[1] Ulman Lindenberger,[1] Bernhard Hommel,[2] Gisa Aschersleben,[2] Wolfgang Prinz,[2] and Paul B. Baltes[1]

[1]Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany, and [2]Max Planck Institute for Psychological Research, Munich, Germany

ABSTRACT—*Two-component theories of intellectual development over the life span postulate that fluid abilities develop earlier during child development and decline earlier during aging than crystallized abilities do, and that fluid abilities support or constrain the acquisition and expression of crystallized abilities. Thus, maturation and senescence compress the structure of intelligence 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 aspect of processing, predicted fluid intelligence beyond processing speed in old age but not in childhood, suggesting that the causes of more compressed functional organization of intelligence differ between maturation and senescence. Research on developmental changes in functional brain circuitry may profit from explicitly recognizing transformations in the organization of intellectual abilities and their underlying cognitive processes across the life span.*

Spearman (1904) discovered the ubiquitous positive intercorrelations among intelligence tests. Since his work, most researchers in the field of intelligence have viewed the structure of intelligence as static (see Carroll, 1993, and Sternberg, 1994, for overviews), overlooking possible developmental transformations in the organization of intellectual abilities and their underlying information processing and neurobiological mechanisms.

Bernhard Hommel is now at Leiden University, Leiden, The Netherlands. Address correspondence to Shu-Chen Li, Ulman Lindenberger, or Paul B. Baltes, Center for Lifespan Psychology, Max Planck Institute for Human Development, D-14195 Lentzeallee 94, Berlin, Germany; e-mail: shuchen@mpib-berlin.mpg.de, seklindenberger@mpib-berlin.mpg.de, or sekbaltes@mpib-berlin.mpg.de.

A DYNAMIC VIEW OF INTELLECTUAL DEVELOPMENT ACROSS THE LIFE SPAN

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 itself throughout life. Finding stronger correlations between subtests of intelligence in children than in adolescents, early developmentalists (e.g., Garrett, 1946) suggested that a general ability gradually differentiates into fairly distinct aptitudes during maturation. This notion was later extended to cover the life span. Specifically, the *differentiation-dedifferentiation hypothesis* (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980; Reinert, 1970) postulated that intellectual abilities are rather undifferentiated in childhood; undergo differentiation during maturation, leading to a multifaceted ability structure that remains largely invariant during adulthood; and become undifferentiated again (*dedifferentiation*) during senescence.

Three concepts are central in accounting for transformations in the organization of intellectual abilities across the life span. The first is the concept of two related facets of intelligence that define the continuum from *fluid* abilities, which are presumed to be primarily biology based, to *crystallized* abilities, which presumably depend more on experience or knowledge (Cattell, 1971; Horn, 1968, 1970). A conceptually similar distinction is that between fluid *cognitive mechanics* and crystallized *cognitive pragmatics*[1] (Baltes et al., 1998).

The second central concept is 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 concept 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 among 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 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 life span than in adulthood.

AIMS OF THE PRESENT STUDY

In light of recent evidence showing differences in functional cortical organization during childhood development (see Johnson, 2001, for review) and aging (see Cabeza, 2002, and Reuter-Lorenz, 2002, for reviews), as well as differences in genetic contributions to intelligence across the life span (see Plomin & Spinath, 2002, for review), behavioral research on life-span transformations in the organization of intellectual abilities reaches another level of relevance. Parallels between transformations of cognitive functioning 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 life-span trajectories have accumulated (see Horn, 1970, and Horn & Noll, 1997, for reviews), the differentiation-dedifferentiation phenomenon per se has rarely been investigated directly. Examining transformations across the life span requires a broader spectrum of tasks and a broader age span than has been previously covered. So far, most studies have 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 intellectual development with inquiries about information processing correlates of intelligence, although integration of psychometric and experimental approaches has been pursued in research on adult cognition and aging (see Craik & Salthouse, 2000, and 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., degree of performance stability, resulting from less processing 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 attenuation of 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 how processing robustness and its relations to intellectual abilities vary across the life span.

In the present research, we aimed to address some of these limitations. Fifteen psychometric tests measuring fluid and crystallized abilities and 10 basic experimental cognitive tasks measuring processing speed and robustness were administered to a population-based sample covering a wide age range. Specifically, we directly focused on life-span differences in the strength of coupling (covariation) between different intellectual abilities and the speed and robustness of their underlying information processing mechanisms.

METHOD

Sample

A life-span sample with 356 participants 6 to 89 years old was randomly drawn from a parent sample of 1,920 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 change across the life span, for the age stratification we used 1-year, 4-year, and 3-year age bins for ages 6 to 15, 16 to 59, and 60 to 89, respectively. Excluding participants who missed multiple testing sessions, who had severe health problems, or whose data contributed to multivariate nonnormality, 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 differences in the couplings between intellectual abilities and cognitive processes across the life span, we divided the sample into continuous age groups covering six

[1]In linking Cattell and Horn's theory of fluid and crystallized intelligence to life-span and cognitive psychology, Baltes (1987) distinguished between two domains of intellectual functioning: cognitive mechanics, which refers to information processing mechanisms implementing the fluid abilities, and cognitive pragmatics, which refers to culture- and knowledge-related applications of the cognitive mechanics. The distinction between cognitive mechanics and pragmatics generalized the theory beyond the psychometric tradition to encompass theories and findings from research in evolutionary biology, anthropology, experimental cognitive psychology, and expertise, among other areas (for further details, see Baltes et al., 1998).

life periods: childhood (6–11 years), adolescence (12–17 years), early adulthood (18–35 years), middle adulthood (36–55 years), late adulthood (56–69 years), and old age (70–89 years).

Psychometric Measures

A battery of 15 psychometric tests from the Berlin Aging Study was 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 are (a) 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; (b) Memory, measured by Activity, Paired Associate, and Text Recalls tests; (c) Reasoning, measured by tests of Figural Analogies, Letter Series, and Practical Problems; (d) Verbal Knowledge, measured by the Practical Knowledge, Spot-a-Word, and Vocabulary tests; and (e) Verbal Fluency, measured by the tests of naming names of animals, red things, and words beginning with *s*. The first three abilities are indicators of fluid intelligence (*gf*), and the last two define 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 literature on childhood development (e.g., Fry & Hale, 1996) and aging (see Craik & Salthouse, 2000, for review). By piecing together results from developmental and aging studies, researchers have conceptualized processing speed as an information processing resource underlying intellectual development across the life span (e.g., Cerella & Hale, 1994; Kail & Salthouse, 1994). For the present study, we adapted 10 basic experimental cognitive tasks (BECTs) to assess the speed and robustness of a range of processes: visual search, response competition, long-term and short-term memory search, and choice reactions. The 10 tasks were organized in pairs, each pair consisting of 2 conditions (tasks) that varied in cognitive load and assessed one of these processes.

The stimuli used in the visual search tasks 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 a filled circle (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 to assess response competition. In the compatible condition, the color of the distractors was the same as the color of the target, whereas in the incompatible condition, the color of the distractors not only differed from the color of the target, but also was identical to the color of a stimulus that required a competing response.

Memory search was measured by two pairs of tasks. The first involved matching the names or the physical identities 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 indicated 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 the letters in order to indicate whether the letters shared identical names (e.g., *Aa* and *Bb*). The second pair of tasks assessing memory involved spatial patterns. The stimuli were pairs of circles, each circle having three dots on its circumference. The participants indicated 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; in the memory condition, the two items in a pair were presented with a 3,000-ms delay between them. Simple and choice reaction tasks formed the fifth pair of BECTs.

RESULTS

Age Gradients of Intellectual Abilities, Processing Speed, and Processing 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 ($M = 50$, $SD = 10$). The fitted curves were based on the group means of the 31 age bins and were derived from a combined exponential growth-and-decline function for reaction times (RTs; cf. Cerella & Hale, 1994) that was modified for accuracy, speed, and robustness data. Across all measures, the fitted curves accounted for substantial portions of variance (r^2 ranged from .73 to .97, $M = .89$). As might be expected given the hybrid nature of the fluency measures, the age gradient of verbal fluency fell in between the gradients of fluid abilities and verbal knowledge, but closer to that of verbal knowledge. Given the a priori theoretical distinction and the differential age gradients of fluid and crystallized abilities in our data, we also computed separate composite scores of fluid and crystallized intelligence.

In addition to simply examining RTs, we transformed the RTs of each of the BECTs into processing speed by taking the inverse of RT (i.e., 1/RT), a measure that 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 the *T*-score metric. 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 intra-individual trial-by-trial RT fluctuations.

Our overall results support the distinction between fluid and crystallized intelligence, as well as the idea about their differential trajectories across the life span, although it is important to keep in mind the caveat that cross-sectional age differences are only approximations of true longitudinal growth and decline (Molenaar, Huizenga, & Nesselroade, 2003). The age gradients of fluid and crystallized intelligence showed a lead-lag pattern, with fluid intelligence exhibiting earlier growth and decline than crystallized intelligence (Figs. 1a and 1c).

RTs of the BECTs showed various rates of growth and decline (Fig. 1b). As expected, the more difficult tasks (e.g., conjunction visual search) showed steeper growth and decline than the easier tasks (e.g., simple reactions). Furthermore, age gradients of processing speed and processing robustness corresponded very closely to the gradient of the relatively more biology-based fluid intelligence, but less closely to the

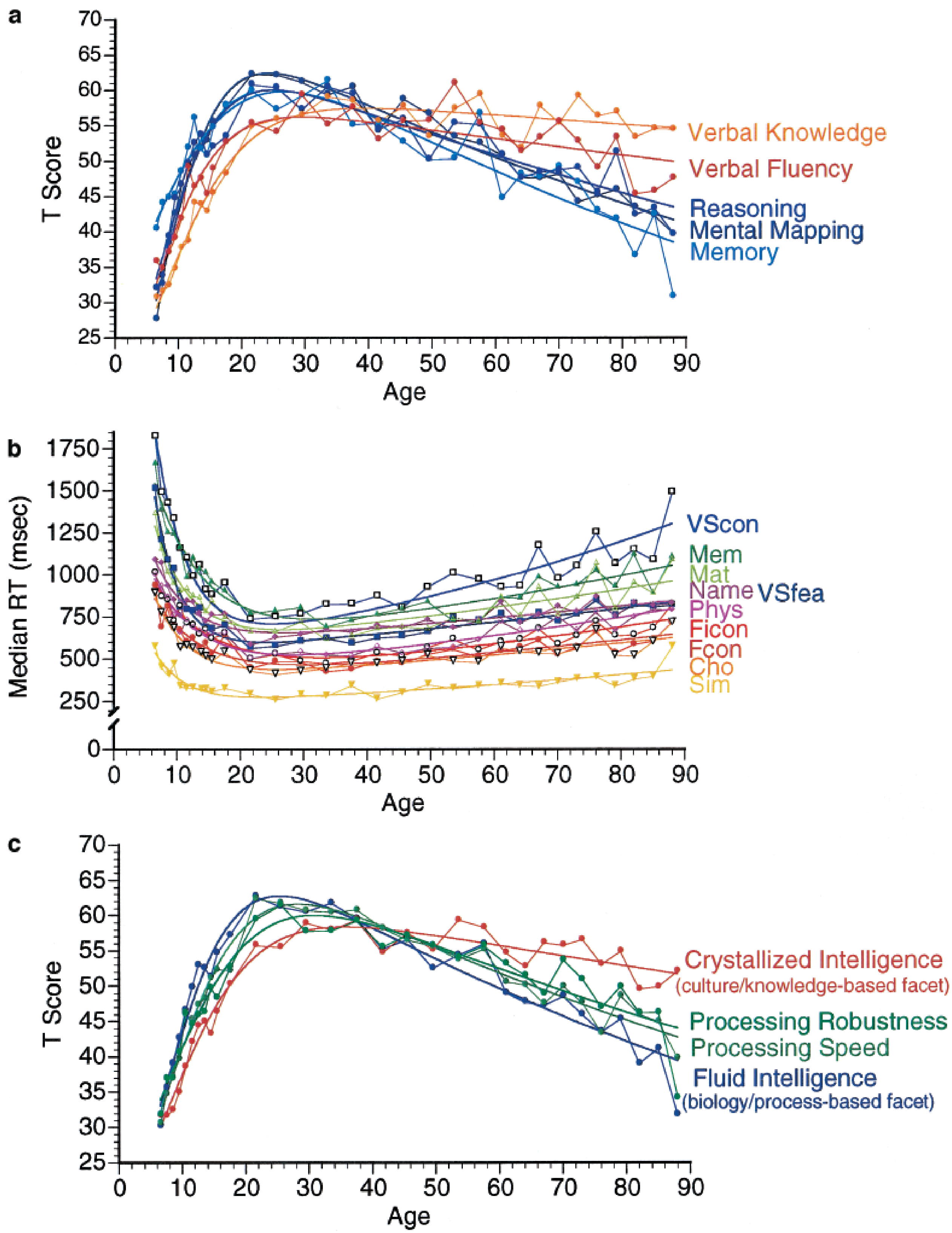

Fig. 1. Age gradients of intellectual abilities and cognitive processes. The graphs show group means and estimated age gradients of five intellectual abilities (a), group means and estimated age gradients of reaction times (RTs) for 10 basic experimental cognitive tasks (b), and age gradients of fluid intelligence, crystallized intelligence, processing speed, and processing robustness (c). VScon = visual conjunction search; Mem = memory-matching task; Mat = pattern-matching task; Name = Posner task, name-identity condition; VSfea = visual feature search; Phys = Posner task, physical-identity condition; Ficon = flanker task, incompatible condition; Fcon = flanker task, compatible condition; Cho = choice RT task; Sim = simple RT task.

gradient of the more knowledge-based crystallized intelligence (Fig. 1c). Maximum processing speed, processing robustness, and fluid intelligence were achieved by individuals in their mid 20s. Decrements were already visible by the mid 30s. The maximum crystallized intelligence scores were achieved by individuals in their 40s, and crystallized intelligence scores remained relatively stable until old age, at which point they also declined (beyond 70 years of age, $r_{\text{age, gc}} = -.45$, $p < .01$).

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. Fluid intelligence manifests itself not only in measures of the efficiency of mental operation, but also in accuracy-based measures of reasoning and memory abilities. The close correspondence of the age gradients of processing robustness and fluid intelligence is the first evidence for the relationship between the development of intellectual functioning and processing robustness over the life span.

Individual differences in processing speed and robustness were highly correlated. However, processing robustness also showed unique predictive validity. 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 for crystallized intelligence. Moreover, processing robustness predicted old people's chronological age above and beyond the variance accounted for by processing speed (Table 1). Intriguingly, all of these effects were unique to aging, but not present during childhood development.

Differences in the Correlations Between Intellectual Abilities and Information Processing Across the Life Span

We compared the strengths of coupling between intellectual abilities and processing speed in adjacent age groups covering the six life periods. First, we examined whether between-individuals variance was equivalent across age groups. Tests of homogeneity (Cochran's *C* and Bartlett-Box *F*) showed that except for the composite memory score and processing speed derived from one BECT (i.e., the pattern-matching task), homogeneity of between-individuals variance obtained across the six age groups. Furthermore, the pattern of differences in between-subjects variance in these two measures did not statistically favor children or older adults for exhibiting stronger correlations among variables than younger adults. When adjacent age groups were combined to produce larger sample sizes per group, the results remained similar to those with the six age groups that we present here. Reliability tests also showed that estimates of internal consistency of most of the psychometric and experimental measures, except Activity Recall, were comparable across age groups (Cronbach's α ranged from .80 to .96 for RT measures and from .65 to .95 for all psychometric tests except the memory tests, for which Cronbach's α ranged from .40 to .85). Excluding Activity Recall, which was less reliably measured than all the other tests 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 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, which shows only two extracted dimensions) than in adolescence, young adulthood, and middle adulthood (Fig. 2b, which shows five extracted dimensions). Relatedly, the amount of variance accounted for by the first principal component was larger at both ends than at the middle of the life span, 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 adulthood, and middle adulthood ($z = 3.7$).

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 ($z = 1.9$; see Fig. 2e). 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. The pattern of stronger coupling with processing speed at both ends of the life span than at the middle was similar to that observed for fluid intelligence. In the case of crystallized intelligence, significant correlations with processing speed were found in childhood, late adulthood, and old age.

The shared variance between processing speed and chronological age in predicting intelligence was examined more closely. The amount of predicted variance in fluid (Fig. 3a) and crystallized (Fig. 3b) intelligence that was shared between processing speed and age was highest in childhood and lowest in adulthood. With respect to predicting fluid intelligence, all amounts of explained variance, with the exception of unique age variance and the shared variance in early and middle adulthood, were significant beyond the .05 level. The overall amounts of predicted variance were smaller for crystallized

TABLE 1

Results of Variance Component Analysis Showing the Unique Predictive Validity of Processing Robustness in Late Adulthood and Old Age (55–89 years).

	Outcome variable		
Predictor	Fluid intelligence	Crystallized intelligence	Chronological age
Processing speed	4.1 ($p < .01$)	4.4 ($p < .01$)	0.6 ($p > .38$)
Processing robustness	4.7 ($p < .01$)	0.1 ($p > .74$)	6.5 ($p < .006$)
Shared speed and robustness	28.7 ($p < .001$)	13.3 ($p < .01$)	41.9 ($p < .001$)
Total	37.5 ($p < .001$)	13.5 ($p < .01$)	48.8 ($p < .001$)

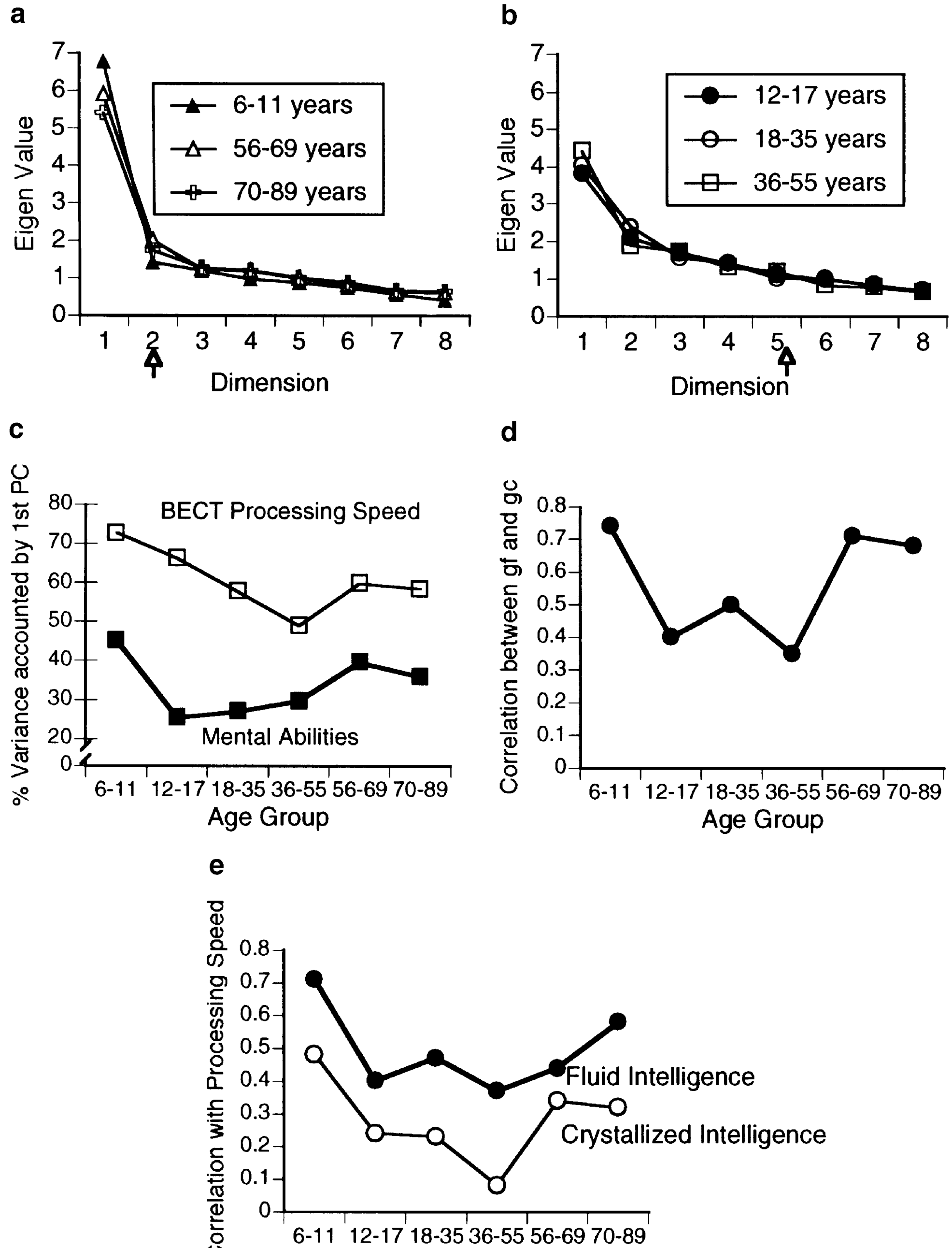

Fig. 2. Differences in the coupling between intellectual abilities and processing speed across the life span. In the scree plots of the principal component analyses of intellectual abilities (a, b), the arrows indicate the estimated number of dominant principal components (i.e., components with eigenvalues > 1). The graph in (c) shows the percentages of variance in processing speed in 10 basic experimental cognitive tasks (BECTs) and 15 measures of intellectual abilities accounted for by the first principal component (PC) in the six age groups. The correlations between fluid and crystallized intelligence (d) and between processing speed and these two facets of intelligence (e) are shown for the same six age groups.

intelligence than for fluid intelligence. These results suggest that factors contributing to transformations in the organization of intellectual abilities across the life span may, in part, also contribute to the age gradients of these abilities.

As a metric of physical time, chronological age by itself does not have any direct causal influence on development, although it is an accepted proxy. The central task of developmental research is to explicate the role of age by specifying endogenous and exogenous processes bearing direct functional relations with development over time. 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, experiential influences on

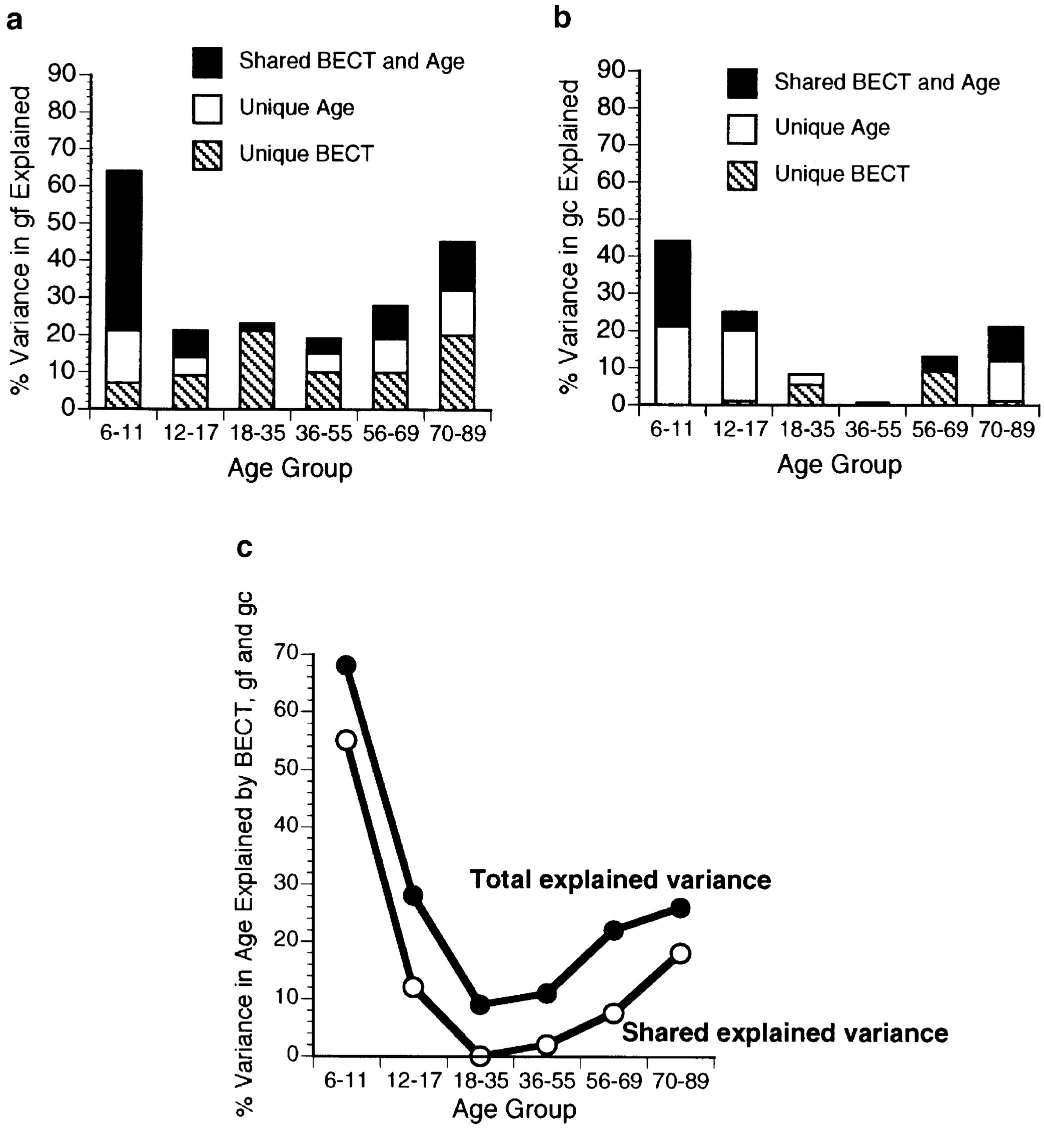

Fig. 3. Results from variance component analyses showing differences in the amount of shared variances across the life span. The graphs in (a) and (b) show the unique and shared contributions of age and processing speed in the basic experimental cognitive tasks (BECTs) in predicting fluid intelligence (*gf*) and crystallized intelligence (*gc*), respectively. The graph in (c) shows the percentages of total and shared variance in chronological age predicted by processing speed, fluid intelligence, and crystallized intelligence.

knowledge acquisition and expression) processes as reflected in our entire set of measures predicted individual differences in chronological age. Specifically, we examined whether the amount of shared variance between internal biology-based and external culture-based influences was larger at both ends of the life span than at the middle. Results from a variance component analysis, with processing speed, fluid intelligence, and crystallized intelligence predicting chronological age (Fig. 3c), showed that 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 life span, compared with other life periods, 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 life-span theories (e.g., Baltes et al., 1998; Horn, 1968; Reinert, 1970), we found that the couplings between fluid and crystallized intelligence (or, alternatively, between cognitive mechanics and pragmatics) and their constituent cognitive processes were stronger at both ends of the life span than at the middle (Figs. 2 and 3c). These results indicate more compressed functional organization of intellectual abilities and cognitive processes in childhood and old age than in adulthood. In particular, these findings support the dynamic differentiation-dedifferentiation view of intellectual development across the life span. Our behavioral data mirror recent cognitive neuroscience findings indicating that cortical functional organization is dynamic, increasing in processing specificity during maturation (Johnson, 2001), but decreasing in specificity (e.g., Logan, Sanders, Snyder, Morris, & Buckner, 2002) or increasing in compensatory integration during senescence (see Cabeza, 2002, and Reuter-Lorenz, 2002, for reviews).

Furthermore, we also found evidence that the age gradients for information processing speed, processing robustness, and fluid intelligence correspond closely (Fig. 1c). Overall, processing speed and robustness are more closely related with fluid than with crystallized intelligence, particularly during maturation and senescence (Fig. 2e). Our results accord with previous research on cognitive aging showing that fluid abilities correlated more with basic sensory processing and crystallized abilities more with socio-biographical predictors (Lindenberger & Baltes, 1997), and thus provide further support for the idea that these two facets of intelligence differentially reflect neurobiological and sociocultural influences on intellectual development.

The life-span perspective 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 than at the middle of the life span. Also, the organization of intellectual functioning was less differentiated in the maturation and senescence portions of the life span than in the middle. These similarities notwithstanding, our results also demonstrated that senescence is not merely the mirror reversal of maturation: Processing robustness was predictive of fluid intelligence and chronological age only in late adulthood and old age, not in childhood. This result is consistent with other recent findings suggesting that decreased processing robustness in old age might reflect attenuation of brain integrity due to aging (e.g., Hultsch et al., 2000; Li, Aggen, 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 at the information processing or neurobiological level, or both (Li, Lindenberger, & Sikström, 2001).

Two limitations of the present study are pertinent to life-span 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 confirmatory factor analysis. Relative to confirmatory approaches, these exploratory analyses yield cruder comparisons of age differences in factorial structure per se. Second, our conclusions rest 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., 2003, for relevant proofs and simulations). Thus, additional longitudinal studies with larger samples are needed to examine the dynamics, as well as the correspondences between age differences and age changes, of intelligence structure in greater detail (cf. Ghisletta & Lindenberger, in press; McArdle et al., 2002).

In conclusion, the results of this study make a clear case for more careful considerations of how the correlations among intellectual abilities and their underlying cognitive processes vary across the life span. In a related vein, recent theories of neurocognitive developmental disorders also stress developmental dynamics as a key to understanding cognitive impairments (Karmiloff-Smith, 1998). As cognitive neuroscience rapidly advances toward unraveling brain functions by using cognitive tasks and individual differences in cultural, experiential influences (Hedden et al., 2002; Johnson, 2001; Li, 2003; Paulesu et al., 2001) to probe the functionalities of various brain circuitries, the behavioral phenomena of transformations in the functional organization of intellectual abilities and cognitive processes across the life span should be acknowledged, further explored, and exploited.

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REFERENCES

Balinsky, B. (1941). An analysis of the mental factors of various groups from nine to sixty. *Genetic Psychology Monographs*, *23*, 191–234.

Baltes, P.B. (1987). Theoretical propositions of life-span developmental psychology: On the dynamics between growth and decline. *Developmental Psychology*, *23*, 611–626.

Baltes, P.B., Cornelius, S.W., Spiro, A., Nesselroade, J.R., & Willis, S.L. (1980). Integration versus differentiation of fluid/crystallized intelligence in old age. *Developmental Psychology*, *6*, 625–635.

Baltes, P.B., Lindenberger, U., & Staudinger, U.M. (1998). Life-span theory in developmental psychology. In W. Damon (Ed.-in-Chief) & R.M. Lerner (Vol. Ed.), *Handbook of child psychology: Vol. 1. Theoretical models of human development* (pp. 1029–1041). New York: Wiley.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults. *Psychology and Aging*, *17*, 85–100.

Carroll, J.B. (1993). *Human cognitive abilities: A survey of factor analytic studies*. New York: Cambridge University Press.

Cattell, R.B. (1971). *Abilities: Their structure, growth and action*. Boston: Houghton Mifflin.

Cerella, J., & Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychologica*, *86*, 109–197.

Craik, F.I.M., & Salthouse, T.A. (Eds.). (2000). *The handbook of aging and cognition*. Mahwah, NJ: Erlbaum.

Deary, I.J. (2001). Human intelligence differences: Towards a combined experimental-differential approach. *Trends in Cognitive Sciences*, *5*, 164–170.

Fry, A.R., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence. Evidence for a developmental cascade. *Psychological Science*, *7*, 237–241.

Garrett, H.E. (1946). A developmental theory of intelligence. *American Psychologist*, *1*, 372–378.

Ghisletta, P., & Lindenberger, U. (in press). Age-based structural dynamics between perceptual speed and knowledge in the Berlin Aging Study: Direct evidence for ability dedifferentiation with age. *Psychology and Aging*.

Hedden, T., Park, D.C., Nisbett, R., Ji, L.J., Jing, Q.C., & Jiao, S.L. (2002). Cultural variation in verbal versus spatial neuropsychological function across the life span. *Neuropsychology*, *16*, 65–73.

Horn, J.L. (1968). Organization of abilities and the development of intelligence. *Psychological Review*, *75*, 242–259.

Horn, J.L. (1970). Organization of data on life-span development of human abilities. In L.R. Goulet & P.B. Baltes (Eds.), *Life-span developmental psychology: Research and theory* (pp. 423–466). New York: Academic Press.

Horn, J.L., & Noll, J. (1997). Human cognitive capacities: Gf-Gc theory. In D.P. Flanagan, J.L. Genshaft, & P.L. Harrison (Eds.), *Contemporary intellectual assessment* (pp. 53–91). New York: Guilford Press.

Hultsch, D.F., MacDonald, S.W.S., Hunter, M.A., Levy-Bencheton, J., & Strauss, E. (2000). Intraindividual variability in cognitive performance in older adults: Comparison of adults with mild dementia, adults with arthritis, and healthy adults. *Neuropsychology*, *14*, 588–598.

Johnson, M.H. (2001). Functional brain development in humans. *Nature Review Neuroscience*, *2*, 475–483.

Jones, H.E., & Conrad, H.S. (1933). The growth and decline of intelligence: A study of a monogenous group between the ages of ten and sixty. *Genetic Psychology Monographs*, *13*, 233–297.

Kail, R., & Salthouse, T.A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, *86*, 199–225.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences*, *2*, 389–398.

Li, S.-C. (2003). Biocultural orchestration of developmental plasticity across levels: The interplay of biology and culture in shaping the mind and behavior across the lifespan. *Psychological Bulletin*, *129*, 171–194.

Li, S.-C., Aggen, S.H., Nesselroade, J., & Baltes, P.B. (2001). Short-term fluctuations in elderly people's sensorimotor functioning predict text and spatial memory performance: The MacArthur Successful Aging Studies. *Gerontology*, *47*, 100–116.

Li, S.-C., Lindenberger, U., & Sikström, S. (2001). Aging cognition: From neuromodulation to representation. *Trends in Cognitive Sciences*, *5*, 479–486.

Lindenberger, U. (2001). Lifespan theories of cognitive development. In N.J. Smelser & P.B. Baltes (Eds.-in-Chief), *International encyclopedia of the social and behavioral sciences* (pp. 8848–8854). Oxford, England: Elsevier Science.

Lindenberger, U., & Baltes, P.B. (1997). Intellectual functioning in old and very old age: Cross-sectional results from the Berlin Aging Study. *Psychology and Aging*, *12*, 410–432.

Logan, J.M., Sanders, A.L., Snyder, A.Z., Morris, J.C., & Buckner, R.L. (2002). Under-recruitment and non-selective recruitment: Dissociable neural mechanisms associated with aging. *Neuron*, *33*, 827–840.

McArdle, J.J., Ferrer-Caja, E., Hamagami, F., & Woodcock, R.W. (2002). Comparative longitudinal structural analyses of the growth and decline of multiple intellectual abilities over the life span. *Developmental Psychology*, *38*, 115–142.

Molenaar, P.C.M., Huizenga, H.M., & Nesselroade, J.R. (2003). The relationship between the structure of inter-individual and intra-individual variability: A theoretical and empirical vindication of developmental system theory. In U.M. Staudinger & U. Lindenberger (Eds.), *Understanding human development: Dialogues with lifespan psychology* (pp. 339–360). Dordrecht, The Netherlands: Kluwer.

Paulesu, E., Demonet, J.F., Fazio, F., Cappa, S.F., Cossu, G., Frith, C.D., & Frith, U. (2001). Dyslexia: Cultural diversity and biological unity. *Science*, *291*, 2165–2167.

Plomin, R., & Spinath, F.M. (2002). Genetics and general cognitive ability (g). *Trends in Cognitive Sciences*, *6*, 169–176.

Rabbitt, P., Osman, P., Moore, B., & Stollery, B. (2001). There are stable individual differences in performance variability, both from moment to moment and from day to day. *Quarterly Journal of Experimental Psychology A*, *54*, 981–1003.

Reinert, G. (1970). Comparative factor analytic studies of intelligence throughout the life span. In L.R. Goulet & P.B. Baltes (Eds.), *Life-span developmental psychology: Research and theory* (pp. 476–484). New York: Academic Press.

Reuter-Lorenz, P.A. (2002). New visions of the aging mind and brain. *Trends in Cognitive Sciences*, *6*, 394–400.

Salthouse, T.A. (1993). Speed and knowledge as determinants of adult age-differences in verbal tasks. *Journals of Gerontology: Psychological Sciences*, *48*, P29–P36.

Schaie, K.W., Maitland, S.B., Willis, S.L., & Intrieri, R.C. (1998). Longitudinal invariance of adult psychometric ability factor structures across 7 years. *Psychology and Aging*, *12*, 8–20.

Spearman, C. (1904). General intelligence, objectively determined and measured. *American Journal of Psychology*, *15*, 201–293.

Sternberg, R.J. (Ed.). (1994). *Encyclopedia of human intelligence*. New York: Macmillan.

Welford, A.T. (1981). Signal, noise, performance and age. *Human Factor*, *23*, 97–109.

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