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# Stages of Brain and Cognitive Maturation

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Epstein (1974a, 1986) and McCall (1988; McCall, Meyers, Hartman, & Roche, 1983) presented discrepant findings regarding the presence of stages in brain and cognitive maturation, as described in Piagetian theory. This article questions whether their variables (e.g., skull circumference and global mental test scores) are appropriate indices from which to make such conclusions. Evidence from direct brain measurements (e.g., the quantitative electroencephalogram [QEEG]) and other neurobiological indices provides stronger support for the conclusion that regional brain maturation exhibits growth spurts and plateaus. The specific neuropsychological functions represented by regional QEEG maturation data give a composite picture of brain growth that is consistent with Piagetian theory.

Epstein (1974a, 1986) and McCall (1988; McCall, Meyers, Hartman, & Roche, 1983) reviewed studies on skull circumference and mental test performance to estimate the probable relationships between brain and cognitive maturation. Epstein reported that skull circumference and mental test performance (in independent, cross-sectional samples) were correlated over the first 17 years of postnatal development. Furthermore, he reported that brain and cognitive maturation proceeded by incremental spurts and plateaus, with three growth cycles starting at 1, 6, and 10 years of age, respectively. McCall found that he could not replicate these correlations in a longitudinal sample (same variables, within subjects). Consequently, he questioned the validity and usefulness of brain measurements (i.e., inferred from skull circumference) and their application in the design of educational programs.

Epstein (1974a, 1986) and McCall (1988; McCall et al., 1983) opened important discussions concerning the applicability of modern neuroscience data in the design of educational programs. It is clear that both identified critical issues that make the relationships between brain and mental growth difficult to interpret. Because most investigators in this area are reevaluating previously published data, there is little hope that many desirable or critical variables were used in a single research report. Given this limitation, the variables used by Epstein and McCall may not provide essential distinctions for relating brain and cognitive growth.

There is evidence that skull circumference may be a weak index for cerebral maturation (Thatcher, 1990). Furthermore, skull circumference cannot reveal the status of regional brain functions that underlie cognitive skills. Global mental test scores reflect averages of many specific cognitive skills that could, more appropriately, be attributed to functions of regional brain systems. Correlations between skull and mental test measurements do not provide sufficiently detailed information concerning brain or cognitive growth to warrant prospective decisions. Resolution of the issues raised by Epstein (1974, 1986) and McCall (1988; McCall et al., 1983) might well be found in direct measurements of regional brain growth and specific cognitive skills that emphasize the neuropsychological dependencies we assume in brain–cognition correlations.

## Brain Systems and Maturation

The brain processes involved in mental function are composed of large anatomical regions that are organized hierarchically into executive, cross-modal, perceptual, and imaging functions. A working model for these functions can be found in systematic discussions by Pribram (in press). A number of recent studies have suggested that cerebral and cognitive maturation are intimately correlated. Rates of cerebral maturation have been estimated from cross-sectional studies of skull size, the electroencephalogram, cortical thickness, cortical volume, and nerve cell densities (Epstein, 1974a, 1974b, 1980, 1986; Hudspeth, 1985; Hudspeth, & Pribram 1990; Hudspeth & Thatcher, 1987; Thatcher, 1990; Thatcher, Giudice, & Walker, 1987). This diverse set of measurements provides consistent evidence that cerebral maturation proceeds in a discontinuous manner, characterized by spurts and plateaus.

## The Regional EEG

The human electroencephalogram (EEG) is a record of brain electrical activities that can routinely be obtained from subjects of any age. Computer quantification of changes in the EEG frequency spectrum (QEEG) has allowed investigators to establish statistical relationships between regional brain states and maturity (Hudspeth, 1985; Hudspeth & Pribram, 1990; Hudspeth & Thatcher, 1987; Matousek & Petersen, 1973; Thatcher, 1990; Thatcher et al., 1987). QEEG measures have been shown to have high reliability and validity as indices for both normal and abnormal brain functions.

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We (Hudspeth, 1985; Hudspeth & Pribram, 1990; Hudspeth & Thatcher, 1987) described a detailed pattern of neuropsychological maturation that would be expected on the basis of incremental QEEG maturation curves obtained from different regions of the human brain. Our analysis showed that brain maturation exhibits five cycles (i.e., spurts and plateaus) over the first 21 years of postnatal development and that the temporal sequence of maturation in specific regions of the brain is consistent with cognitive development as outlined in the work of Piaget and Inhelder [Inhelder & Piaget, 1958; Piaget, 1950, 1971]. In the remainder of this article, we survey these findings.

## Method

Matousek and Petersen (1973) published in the first set of QEEG normative data, based on four bands of the EEG frequency spectrum. All details concerning the methods, nature and selection of subjects, recording, and data analysis may be found in their original work. EEG records were obtained from 561 normal children aged 1 to 21 years, using four bilateral locations of the cortex (e.g., F7–T3, F8–T4, T3–T5, T4–T6, Cz–C3, Cz–C4, P3–O1, P4–O2). We (Hudspeth, 1985; Hudspeth & Pribram, 1990) calculated first-order increment curves using the sum of squared vector lengths for four QEEG frequencies ($\delta$ = 1.5–3.5; $\theta$ = 3.5–7.5; $\alpha$ = 7.5–12.5; $\beta$ = 12.5–25; all in cycles/second), to derive single maturation trajectories for each brain region.

The regional location of QEEG recording electrodes provides essential information concerning the functional significance of QEEG maturation. The parieto-occipital data (PO: O1–P3 and O2–P4) are most likely to reflect perceptual and cross-modal functions of the visual and visuospatial systems. The temporo-temporal data (TT: T3–T5 and T4–T6) are most likely to reflect perceptual and cross-modal functions of the auditory and visuoauditory systems. The centro-central data (CC: Cz–C3 and Cz–C4) are most likely to reflect image functions of the sensorimotor systems. The fronto-temporal data (FT: F7–T3 and F8–T4) are most likely to reflect executive and cross-modal functions of the frontal and auditory systems, especially those related to language production. The incremental QEEG maturation curves can, therefore, be taken as an index of maturation for regionally specific neuropsychological functions.

## Results

Figure 1a presents incremental maturation curves (e.g., percentage increment per 6-month period), and Figure 1b shows the cumulative maturation curves (e.g., percentage of adult maturity per 6-month period) for the four brain regions studied. These data can be used as an empirical estimate of growth spurts and plateaus, as suggested by Piagetian theory.

These analyses provided evidence for five statistically significant stages in QEEG maturation. As can be seen, maturation patterns over the first decade of life (1–10½ years) were synchronized across all brain regions. Beginning with the stirrings of puberty (roughly), maturation of the QEEG recorded from the temporal, central, and frontal regions of the brain shows different onsets and offsets of rapid change. Some synchrony is maturation during this period was observed in the parieto-occipital, temporo-temporal, and central regions between 13 and 17 years of age, although the peaks of maximum change are separated by approximately 1-year intervals.

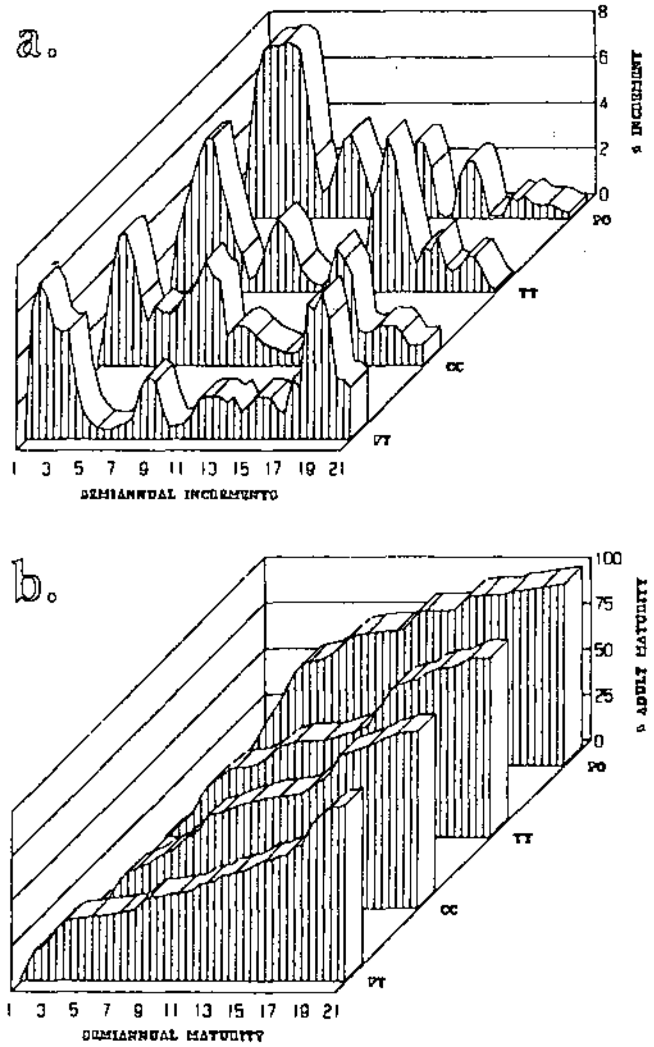


*Figure 1.* Semiannual incremental and maturity curves computed by the direct algorithm. (Panel a represents the semiannual increment curves, and Panel b presents the cumulative semiannual increments to demonstrate the relative rates of growth spurts and plateaus obtained in these analyses. The cumulative maturity curves in Panel b are scaled as the percentage of final adult [i.e., 21 years old] maturation within each of the four brain regions [PO = parieto-occipital, TT = temporo-temporal, CC = centro-central, FT = fronto-temporal].)

However, the fifth stage (18–21 years) was recorded almost exclusively from the frontal electrodes. According to these indices, postpubertal maturation proceeds from the posterior to the frontal areas of the brain. Thatcher et al. (1987) obtained QEEG coherence measurements from an independent sample of children, and their findings are, for all intents, identical to those reported here (Hudspeth & Thatcher, 1987).

Piaget and Inhelder's (Inhelder & Piaget, 1958; Piaget, 1950, 1971) work provides an outline of the ontogeny of cognitive functions in humans. Because they used a finite set of methods, it is entirely possible that different test methods would reveal minor exceptions to the broad outline. However, the evidence for the uneven rates of QEEG maturation that we observed shows that the temporal sequence of Piaget and Inhelder's outline is consistent with stages of cerebral maturation, including neo-Piagetian concepts of postformal, or dialectic, functions (Kramer, 1983; Riegel, 1973, 1975). The correlations between cognitive and cerebral maturation are presented in Figure 2. Figure 2a of Figure 2 presents a summary of the Piagetian outline; and Figure 2b presents the changes in rates of the QEEG plotted against age for various recording locations. As can be seen, Piaget's outline of cognitive maturation corresponds to changes in the rates of QEEG recorded from different brain regions. Because the QEEG data were recorded from a limited number of cortical regions, we can discuss the maturation only of the visuospatial, visuoauditory, sensorimotor, and executive functions, which were the functions specified by the electrode locations.

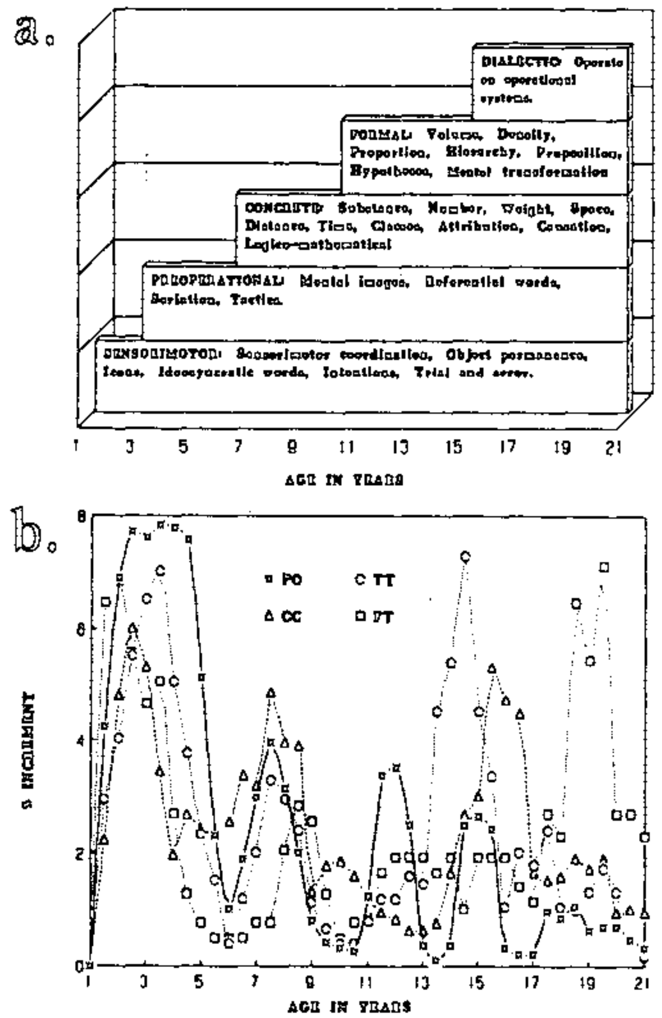


*Figure 2.* Correspondences between Piagetian stages of cognitive (a) and cerebral (b) maturation. (Panel a presents a schematic summary of the perceptual and cognitive skills that are organized during different stages of maturation. Five Piagetian stages are represented along with the theorized age of onset for each: sensorimotor, preoperational, concrete, formal, and dialectic. Brief notes have been appended to each stage to indicate the qualitative type of skills that are presumed to arise in each stage. Panel b presents the semiannual increment curves [direct method] for each brain region [PO = parieto-occipital, TT = temporo-temporal, CC = centro-central, FT = fronto-temporal] to demonstrate the correspondences.)

The sensorimotor period (Figure 2a) appears to be related to rapid maturation in all brain regions (Figure 2b). However, only the executive (e.g., FT) and sensorimotor (e.g., CC) functions exhibit rapid maturation that is limited to this period. The preoperational period appears to coincide with rapid maturation in the visuoacoustic (e.g., TT) function, coupled with an extension from the sensorimotor period of rapid maturation recorded from the visuospatial (e.g., PO) location. The concrete operations period is delimited by maturational increments in all brain regions, with rapid changes in maturation recorded for sensorimotor, visuospatial, visuoacoustic, and executive locations (e.g., CC, PO, TT, FT). The formal operations period appears to coincide with a new period of rapid QEEG maturation recorded from visuospatial (e.g., PO) and visuoacoustic (e.g., TT) locations. Finally, the dialectic period (17–21 years) appears to coincide with an extension from the formal operations period of rapid maturation recorded from increments in visuospatial (e.g., PO) and sensorimotor (e.g., CC) functions in the earlier phase (13–17 years) and by a sizable increase in the rapidity of maturation of the QEEG recorded from the executive location, which had shown minimal increments since the sensorimotor period.

## Conclusion

In view of the evidence, it is reasonable to conclude that brain maturation occurs in "stages" as defined here and as proposed in Epstein's work. Epstein's (1974a, 1974b, 1980, 1986) intent was to outline evidence for brain maturation from different physical indices; his estimates are identical to the earliest stages presented in this article. Nonetheless, there are specific problems that require attention before these facts can be applied to educational planning, and McCall's (1988; McCall et al., 1983) critique serves well to outline these issues. First, as noted, skull circumference is a weak index of brain maturation; the present article has outlined methods based on brain electrical recordings (the QEEG) that are likely to be of greater utility by virtue of being able to differentiate maturation of different brain systems. Second, it is difficult to obtain consistent definitions for cognitive maturation when only overall IQ is used as a measure of cognitive growth. Further difficulties in interpretation arise when different test instruments are used across different age groups. There is a need for a comprehensive cognitive test instrument that can be integrated with indices of brain maturation (i.e., QEEG) and used across the human life span.

We believe that the curves of QEEG maturational rate provide support for a stage model based on inferred correlations between cerebral and cognitive maturation. Nevertheless, there are specific problems in extending the methods for diagnostic or prognostic purposes. First, the continuous rate changes recorded from regional brain maturation are difficult to reconcile with discrete pass–fail test items inherent in Piagetian methodology. Therefore, it is essential to establish parametric behavioral methods for evaluating cognitive skills.

Second, the limited number of QEEG electrodes presented here are not sufficient. The solution to this problem is rather easily obtained by increasing the number of electrodes. In light of the general needs of education, we suggest that some reliable and valid approaches to the problem are possible. QEEG indices exhibit parametric covariation with age ($R^2$ = 99% in our work). Similarly, the developmental trajectories derived from the QEEG are consistent with increments in cognitive maturation. These indices need to be coupled with parametric measures of mental growth, such as those obtained from standardized intelligence test batteries. There is every reason to believe that the correspondences between the indices would be excellent. Perhaps other tests need to be developed, at least, the protocol outlined here can be used as a beginning.

In summary, a caveat: Brain and cognitive maturation have a reciprocal influence on one another. Not only biological variables produce accelerations and decelerations in brain maturation as it is reflected in the QEEG, cognitive experience can also produce brain growth and, perhaps, alter the time course of cognitive development further. Nonetheless, the evidence reviewed here indicates that some very basic biological processes are codependent with experience in determining brain–cognition maturational states.

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