

## Multiple pathways to developmental continuity in infant cognition

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In their provocative opinion piece, Blumberg and Adolph [1] (B&A) argue that inferences regarding cognitive development in infancy that are based on young infants' motor behaviors are misleading. They assert that the motor behaviors, including eye movements and looking time measures traditionally used to characterize cognition between birth and 4 months, are mediated by subcortical mechanisms and, therefore, that this *disconnect* between the cortex and motor behaviors "does not support claims of developmental continuity between early infant and adult cognition." In our view, their thesis (a) is inconsistent with several lines of evidence, and (b) fails to provide a productive path forward in studies of infant development.

Although there are parallels in neural development across species, the bulk of the citations offered by B&A documenting the absence of cortical-motor connectivity come from rodents rather than primates. They cite only one study from humans [2] relevant to their thesis, but that study did not examine visual-motor pathways involving eye-movement control. Instead, it showed that feedback signals between V2 and V1 are absent, suggesting that other feedback pathways are also absent (e.g., from higher-level visual areas mediating complex object recognition and motor behaviors). Crucially, B&A cite no direct evidence of a disconnect between human infant cortex and eye-movement control mechanisms.

Contrary to B&A's thesis that cortical-motor pathways are absent before 4 months of age, structural MRI data from premature newborns indicate that "the corticospinal tract (CST) and optic radiations, which connect motor and visual areas, are among the first tracts in the brain to myelinate." [3] Of course, as B&A note, "anatomical evidence of cortical connectivity with downstream targets does not necessarily mean that these connections contribute to behavior." We agree and recognize that sophisticated mid-brain and brainstem mechanisms can support eye-movements in the absence of cortical influence in animals and that parsimony should guide interpretations of what may only appear to be high-level mechanisms. However, B&A do not provide definitive evidence that subcortical mechanisms in human infants mediate putatively high-level cognitive abilities. We suggest a more agnostic approach that seeks definitive evidence that cortical-motor pathways are indeed absent and that subcortical mechanisms support behaviors typically associated with cortical mechanisms.

In addition, strong statements such as "there is no evidence that the cortex 'speaks' to the brainstem so as to influence motor behaviors", by B&A's own account, only apply to infants

younger than 4 months. Thus, their skepticism about developmental continuity is only relevant to claims about infants under this age. The number of such studies is relatively small (e.g., only a single study on moral development) compared to studies of infants older than 4 months. We are concerned that B&A's skepticism will lead researchers to dismiss the results from all studies, including those in older infants, that utilize traditional looking-time measures of infant sensory, perceptual, cognitive, and social functioning, thereby sending a chilling message to the field. This is especially likely given that this age qualification is not mentioned in the title or the abstract of B&A.

Crucially, if eye-movements and other motor responses in infants younger than 4 months do not reflect cortical involvement in cognition, how do we reconcile the remarkable alignment of behavioral and cortical measures in young infants? Eye-movement evidence of visual acuity in infants is mirrored by EEG signals that clearly arise from visual cortex [4]. Face preferences in newborns based on looking-time measures [5] are also mirrored by EEG signals [6]. And delayed recognition memory assessed with both habituation of looking-time and EEG has been documented in 3-month-olds [7]. In the auditory domain, sucking behaviors that index discrimination of speech contrasts in 1-month-olds [8] are mirrored by fMRI signals in 2-month-olds [9] and EEG signals in 3-month-olds [10]. Finally, sucking behaviors in newborns that index prenatal learning and memory for the maternal voice [11] are consistent with EEG evidence in newborns of maternal voice discrimination [12]. Is all of this converging evidence a mere coincidence? See Box 1 for an alternative hypothesis.

Finally, how can we make progress in the field of infant cognition to resolve these difficult interpretive issues? The logical conclusion from B&A is that definitive evidence for the role of cortical mechanisms in cognition would require "knocking out" a cortical region or a pathway that connects the cortex to a motor-control mechanism. Short of conducting invasive neuroscience (e.g., ECoG or TMS) or relying on data from infants with brain injuries or stroke (which in turn must assume that compensatory reorganization does not render any conclusions misleading), the path forward is largely correlational. Moreover, reliance on animal models to draw inferences, as B&A do, will not work for cognitive domains that are not shared with humans (e.g., language). Thus, for both ethical and practical reasons, we should not reject measures because they are imperfect, but embrace converging behavioral and neural measures to avoid the pitfalls of *rich interpretation*. Inferences about cognitive states of the infant mind are possible even in the absence of invasive methods as long as great care is exercised in drawing parallels across species, content domains, and dependent measures. In conclusion, we agree with B&A that those who make such inferences must be open to criticism if they overinterpret their data, and that they must be willing to accept simpler explanations if new data emerge that are inconsistent with rich interpretation.

[881 words]

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**Box 1. What is the nature of the developmental transition?** B&A assume that a subcortical system has exclusive control of motor behaviors that are falsely attributed to the influence of cortical mechanisms of cognition. According to their thesis, at 4 months of age the subcortical system is incorporated into a cortical system that has been developing in parallel but without

influence over motor behaviors. This runs counter to the principle of feedback in motor-learning and raises a puzzle about what drives the correlation between cortical and subcortical mechanisms if they are developing independently prior to 4 months of age. Missing from B&A is an account of the process of *reorganization* that reconciles their claim of discontinuity within a larger developmental framework. An alternative view – *developmental bootstrapping* – is that a low-level system mediated by subcortical mechanisms becomes modulated by a higher-level cortical system that operates in tandem with the subcortical system. This alternative is consistent with a view of developmental *continuity*. [158 words]

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