COMMENTARY

DYNAMIC FIELD THEORY AND EXECUTIVE FUNCTIONS: LENDING EXPLANATION TO CURRENT THEORIES OF DEVELOPMENT

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ABSTRACT Buss and Spencer's monograph is an impressive achievement that is sure to have a lasting impact on the field of child development. The dynamic field theory (DFT) model, that forms the heart of this contribution, is ambitious in scope, detailed in its implementation, and rigorously tested against data, old and new. As such, the ideas contained in this fine document represent a qualitative advance in our understanding of young children's behavior, and lay a foundation for future research into the developmental origins of executive functioning.

My 4-year-old daughter is very proud of herself—she has learned to ride her two-wheel bike. A few weeks ago, she was very eager to try, so we took her and her bike to a nearby baseball diamond and helped her up onto the seat. She was a bit wobbly at first, but quickly found her balance and got going round and round the diamond on her own, unassisted. She giggled with delight. It was a truly joyous moment. Still, despite her impressive progress, she can't quite ride like her older brother—starting at will, riding consistently straight, stopping at corners, cognizant of cars, potholes, and pedestrians, and heeding the directives of her anxious parents. Put simply, she lacks control.

Inquiry into the psychological nature of control falls under the banner of the executive functions—processes that enable the planning, selection, initiation, stopping, and evaluation of voluntary actions. Executive functions (or EFs) operate on, but are not synonymous with, more elemental perceptual-motor capacities. My daughter, for example, has the necessary

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balance and strength to remain upright on her bike while turning the pedals—she has acquired a basic perceptual-motor skill. Over time though, this skill will (hopefully!) become more controlled. She will learn to plan different routes, adjust her speed given local changes in sidewalk traffic, brake at corners, stop signs, and street crossings, and monitor her turns to avoid painful spills. Adding control will not fundamentally change the mechanics of riding a bike—she will still need to keep her balance and turn the pedals. However, this ability will become subject to a variety of checks and balances and more finely adapted to the demands of her local environment. As such, a developing ability to control voluntary actions plays an indispensable role in my daughter's everyday experience.

Questions concerning the development of EF have enjoyed an enduring fascination, and for good reason. First, the basic phenomena elicited by EF tasks early in development are striking and counterintuitive. In the A-not-B task, for example, 7- to 12-month-old infants face an apparatus with two hiding wells, and watch as an attractive toy is hidden in one of the two wells, termed "A." Following a short delay, infants are allowed to search for the toy and most correctly search at A. Infants then watch as the toy is hidden in the second "B" well. Even though infants see the toy hidden at B, and begin searching only a few seconds later, most search at A. In short, they perseverate by showing persistent use of an old behavior when that behavior is no longer appropriate (Munakata, 1998). Long after they have mastered the A- not-B task, children will show a similar pattern of perseverative behavior in the Dimensional Change Card Sort task (or DCCS; Zelazo, 2006), the focus of this outstanding monograph. In the task, preschoolers sort test cards into bins marked with target cards. In the standard task, test cards match target cards only on a single dimension. Thus, children might sort red trucks and blue boats into bins marked with a blue truck and a red boat. In pre-switch trials, children sort the cards one way (e.g., by color), and typically do just fine. However, in post-switch trials, when they are instructed to switch and sort the cards in a new way (e.g., by shape), most 3.5-year-olds perseverate, by persistently sorting the cards the old way (i.e., by color). The phenomenon is all the more striking as it occurs despite children's apparent knowledge of the correct sorting rule. When asked where boats and trucks go in the new shape game, all children point to correct sorting trays. In spite of this, when asked to sort cards by shape, most 3-year-old children persist in sorting cards by color. The phenomenon is so striking observers are often left completely astounded. I remember administering a DCCS-like task to a young boy under the watchful eye of an older sibling. After perseverating on every post-switch trial, the boy stood up and proudly declared, "Wow, did you see that? I got them all right!" to which his incredulous older sibling replied, "No you didn't! You got them all wrong!" These kinds of counterintuitive behaviors are observed throughout early development and can be explained in terms of underdeveloped EF. In the A-not-B task, for example, infants persist in searching for the toy at A after watching the toy being hidden at B. While it is possible that infants forget seeing the toy hidden at B, clever experimentation has revealed that infants do in fact remember where the toy is. Their counterintuitive behavior thus appears to relate to problems withholding reaches to A. And in the DCCS, 3-year-olds correctly answer questions about new sorting rules, but persist in using old rules. Thus, early in development, simple behaviors like reaching and card sorting are intact but not subject to the regulatory checks and balances that ensure their seamless adaptation to the immediate environment.

A second reason for enduring interest in the development of EF is that individual differences in self-control assessed early in development longitudinally predict important psychological milestones. In one landmark series of studies, Walter Mischel showed that individual differences in young children's ability to forego small immediate rewards in lieu of larger future rewards predicted academic achievement, social adjustment, and coping skills 10 years later in adolescence. Subsequent investigations have indeed confirmed a close relationship between executive functioning skills and intellectual development, both in terms of school readiness and the rate of acquisition of skills such as math (Mischel, Shoda, & Peake, 1988). These data make sense: the ability to focus, hold relevant information in mind, and systematically test and evaluate possible solutions ought to impact how readily children master new intellectual and social challenges. And they do.

A third reason for enduring interest in the development of executive functioning concerns striking parallels between EF and brain development (Diamond, 2002). Broad-scale cortical networks associated with executive functions show continued functional and structural development into early adulthood, akin to the development of EF. Moreover, damage and/or dysfunction in these regions is associated with behaviors reminiscent of those observed in infants and young children. Patients who have undergone remedial lateral prefrontal resection, for example, show high rates of perseveration in card sorting tasks, much like 3.5-year-olds in the DCCS. And primates with experimentally induced lateral prefrontal lesions perseverate in object-search tasks, much like infants in the A-not-B task. Together, these data point to the possibility that the development of EF is related in a fundamental way to the development of particular cortical networks.

Tantalizing behavioral and neurophysiological evidence of this kind calls out for explanation and has contributed to sustained interest in understanding the development of EF. However, in spite of this, many basic issues remain unresolved. First, our understanding of the processes underlying EF remains highly provisional. The origins of this problem stems from the fact that EF, as the term is conventionally used, refers to functions—that is, things that follow from the implementation of a process. Planning is what follows from envisioning a future course of action. Response selection follows from the process of choosing one response over another. Behavioral inhibition follows the successful withholding of a behavior. And so on. The terms themselves are eloquent, and suggestive, but in the end, largely descriptive. They characterize the causal outcome of processes, but not the processes themselves. One approach to this problem has been to ask whether EF tasks—such as response inhibition tasks, working memory tasks, stimulus-response compatibility tasks, switching tasks, and so on—measure a single process or multiple processes. The answer is clear to a point—EF tasks do not appear to measure a single underlying process. Some analyses suggest three underlying processes—working memory, switching, and response inhibition (Miyake et al., 2000)while others suggest two (Hampshire, Parkin, Highfield, & Owen, 2012), with any single result depending in part on the number and type of tasks included in the original test battery, the number of participants included in the sample, and statistical interpretation. However, even if large-scale multivariate decompositions of different behavioral data sets were to converge on a similar set of underlying factors, we would still have only a provisional understanding of the underlying processes that give rise to the observed factor structure. We would be no closer to knowing what shared computation underlies different working memory tasks, for example, or how this computation differs from that underlying different switching tasks. Nor could we be certain that the observed factor structure reflects distinct components of EF. Resulting factors could conceivably be emergent properties of a highly dynamic complex system. Indeed, neuroimaging studies suggest working memory, response inhibition, and switching tasks utilize highly overlapping networks. Distinctions that appear real at a cognitive level of description seem to disappear when we switch to a neurophysiological level of description. These are challenging and fundamental problems that require a move beyond functional descriptions toward an explicit model of underlying computational mechanisms.

In a related vein, questions concerning the development of EF also remain largely unresolved. Foremost among these concern what develops and why. To date, developmentalists have relied heavily on traditional conceptualizations of EF, arguing, for example, that age-related changes in DCCS performance reflect underlying developments in inhibitory control and/or working memory, changes that are, in turn, linked to the maturation of certain brain regions, such as lateral prefrontal cortex. Explanations of this kind are valuable to a degree in that they provide a framework for organizing evidence and directing empirical inquiry. But they are also limited and limiting. First, they don't explain behaviors in terms that are much different than terms that describe the phenomena. To say, for example, that 3-year-olds who perseverate in DCCS fail to inhibit an old way of sorting is a perfectly apt description of their behavior. However, explaining the behavior in the same terms—that is, as a consequence of underdeveloped inhibition—does little to advance our understanding of perseveration. It simply restates the description in explanatory terms. To advance our understanding of behavior, we require explanations that appeal to concepts and/or mechanisms that are distinct from the behaviors being explained. Second, passing the burden of explanation over to a putative process such as brain maturation does more to obscure than illuminate. That the cortex changes dramatically over development is indisputable, as is the protracted development of the prefrontal cortex. Indeed, patterns of brain activity associated with switching, working memory, and inhibitory control change dramatically over development, as revealed by functional neuroimaging methods. However, as compelling as they are, these data are not explanatory. Patterns of brain activity revealed by fMRI say nothing more about process or mechanism than do accuracy or response time, precisely because neuroimaging and behavioral measures alike are simply correlates of unobservable cognitive operations. Thus, evidence that the development of certain brain regions proceeds in parallel with the development of EF does not offer, but requires explanation.

In summary then, questions concerning the development of EF have enjoyed an enduring interest among scholars of psychology for many years, but the field confronts sizable challenges conceptualizing the nature of these changes and their association with changes in brain structure and function. With this in mind, we can begin to appreciate the significance of Buss and Spencer's outstanding monograph. Focusing in particular on changes in behavior revealed by the DCCS task in the preschool years, Buss and Spencer present a computationally based account of EF development and its association with changes in cortical organization. Taking the structure of the human visual system as its point of departure, the dynamic field theory (DFT) model consists of separate perceptual fields that represent colors and shapes and whose activations, or representations, are bound together by a common spatial frame of reference. Activity in these fields is shaped by events in the world, such as the presentation of test cards in the DCCS, as well as prior experience, but is also subject to control via the biasing influence of a dimensional attention system. The model is important because it peels away the many layers of description that have been applied to EF and its development over the years and reveals the inner mechanics of the system. In short, it explains.

Consider, for example, perennial questions concerning the nature of EF. In the hands of Buss and Spencer's DFT model, descriptive characterizations of DCCS performance, such as those based on concepts of inhibition, give way to an explicit characterization of processing dynamics. Sorting by one feature of a test card leads, via incremental learning, to a preference for that feature in subsequent trials. Switching to a new feature therefore requires control, made possible by a biasing signal from the dimensional attention system. If the biasing signal is weak or incoherent, the model's preference for the first feature prevails, and the model perseverates. However, if the biasing signal is strong and coherent, the model switches to the new feature. This characterization of successes and failures in the DCCS goes beyond description and explains behavior in terms that are distinct from the phenomenon under consideration. The model makes explicit how processing might occur during task performance, so that we can begin to understand why rule switching might be associated with behavioral costs and lateral prefrontal cortex activity. Because on switch trials, activation to previously relevant features competes with activation to currently relevant features, the network requires added time to settle on a response, and does so only when top-down intervention sways the battle in favor of the currently relevant features. Thus, compared to repeat trials, responses on switch trials are slow and error prone, and place metabolic demands on the dimensional attention system.

Buss and Spencer's DFT model also provides clear, comprehensive explanation of observable changes in children's DCCS performance over the preschool years. Whereas standard developmental accounts appeal to descriptive concepts in place of detailed explanation, Buss and Spencer's DFT model links age-related change in DCCS performance to putative anatomical and physiological changes in the brain. The core of their account is that connections both within and between regions of the brain become stronger with development. These changes in turn have important consequences for the dynamics of larger systems and the capacity of the model to switch. Young models with weak connectivity have difficulty sustaining working memory like activations within fields and coherent interactions between fields. These models tend to perseverate when sorting criteria change. Older models with strong connectivity, by contrast, show sustained working memory like activity within fields and coherent interactions between fields. These models tend to switch when sorting criteria change. The importance of this account is that it explains age-related changes in DCCS performance in terms that are distinct from its description. Age-related changes in children's capacity to use new rules and inhibit old rules are explained with reference to a putative physiological mechanism as opposed to being turned around and offered up as explanation. While these ideas echo findings from previous modeling research, the current DFT model represents an enormous step forward in our understanding of the development of cognitive flexibility as revealed by the DCCS. First off, the model simulates an impressive set of extant behavioral effects, including performance in the canonical as well negative priming, training, full-change, partial-change, and relational complexity variants of the DCCS. This alone is impressive. But the model goes further, by making a number of predictions concerning the importance of space for DCCS performance that are not made by other theories. These predictions are tested and confirmed (Chapter 5). Taken together then, the work represented in this monograph is in a class of its own, both in its capacity to accommodate extant DCCS data and its capacity to direct new avenues of empirical inquiry.

The implications of Buss and Spencer's model for understanding brain-behavior associations and EF extend well beyond the DCCS though. The model, for example, forces a critical reexamination of switching, inhibition, and working memory as core processes underlying EF. Viewed from the standpoint of the model, switching is not a function computed by an isolated module, or a process that operates independently of inhibition and working memory. Instead, the capacity to switch emerges from a dynamic interplay of multiple fields whose activation is shaped by excitatory, inhibitory, and self-sustaining (or working memory-like) connections. Similarly, the model's capacity to inhibit sorting cards by color is an emergent property of coherent inputs to the color field from the dimensional attention system, as well as inhibitory connections between competing units in the color field. Viewed in this way, behaviors elicited by EF tasks are best thought of as emerging properties of a complex interacting system rather than direct measures of discrete underlying processes. Computational models, like Buss and Spencer's DFT model, are also indispensable for bridging the precarious divide between behavior and the brain. Contrary to popular opinion, neuroimaging methods do not provide a transparent window into the inner workings of the brain. They simply provide a physiological signal that rises and falls over time. The hard work of the cognitive neuroscientist is to explain why signal changes occur the way they do. The standard approach is to compare signal intensity during particular events, such as switch trials, with signal intensity during other events, such as repeat trials. Brain regions in which signal intensity changes across switch and repeat trials are then assumed to be functionally linked in some way with switching. The problem with this approach is that without an adequate characterization of what switching actually consists of, we can't say anything very specific about the function of brain regions associated with this operation. The importance of computational models is that they explicitly characterize unobservable cognitive operations so that we have a mechanistic characterization of what, for example, switching might consist of. Critically though, models generate quantitative predictors that can be used to model variability in physiological and behavioral measures. In a very real sense then, computational models provide a testable account of the unobservable cognitive processes that give rise to observed brain-behavior correlations.

As with any great theory, Buss and Spencer's model has limitations. Some of these call for refinements, others for deeper reflection. It is not clear, for example, how neurotransmission works in the model. It is well known that dopamine and its associated family of receptors play a central role in the function of EF networks, including prefrontal and cingulate cortices. And it is certainly possible to implement these details in models—in fact, models are ideally suited to simulating neuronal networks and their mode of neurotransmission (Frank, Seeberger, & O'Reilly, 2004). These details are noticeably absent in Buss and Spencer's DFT model. Second, the model, as presented, is largely isolated from a larger physical and social environment. The only event in the world the model is able to "comprehend" is the presentation of a test card in the DCCS. The model has no means of even knowing whether its responses are correct or incorrect, let alone whether its "world" is stable and supportive or chaotic and impoverished. While it was clearly not necessary to implement this degree of functionality in order to simulate age-related changes in DCCS performance, its absence limits the model's capacity to serve as a framework for understanding the origins of individual differences in EF early in development. As discussed earlier, individual differences in EF longitudinally predict important developmental milestones including academic achievement, social adjustment, and health-related behaviors. These individual differences are the product of both experiential (e.g., parenting, socioeconomic status, early life stress [Noble, McCandliss, & Farah, 2007]) and genetic (e.g., polymorphic variation, DNA methylation, chromatin remodeling) influences, although the nature of these effects and their possible interaction remain unclear. Computational models have great potential to help unravel these complex issues, but require mechanisms of neurotransmission and social-environmental interaction be specified in more detail than they are in Buss and Spencer's DFT model.

Limitations notwithstanding, Buss and Spencer's monograph is an impressive achievement that is sure to have a lasting impact on the field of child development. The DFT model that forms the heart of this contribution is ambitious in scope, detailed in its implementation, and rigorously tested against data, old and new. As such, the ideas contained in this fine document represent a qualitative advance in our understanding of young children's behavior, and lay a foundation for future research into the developmental origins of executive functioning.

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