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Feedback-based probabilistic category learning is selectively impaired in attention/hyperactivity deficit disorder

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ABSTRACT

Although Attention-Deficit Hyperactivity Disorder (ADHD) is closely linked to executive function deficits, it has recently been attributed to procedural learning impairments that are quite distinct from the former. These observations challenge the ability of the executive function framework solely to account for the diverse range of symptoms observed in ADHD. A recent neurocomputational model emphasizes the role of striatal dopamine (DA) in explaining ADHD's broad range of deficits, but the link between this model and procedural learning impairments remains unclear. Significantly, feedback-based procedural learning is hypothesized to be disrupted in ADHD because of the involvement of striatal DA in this type of learning. In order to test this assumption, we employed two variants of a probabilistic category learning task known from the neuropsychological literature. Feedback-based (FB) and paired associate-based (PA) probabilistic category learning were employed in a non-medicated sample of ADHD participants and neurotypical participants. In the FB task, participants learned associations between cues and outcomes initially by guessing and subsequently through feedback indicating the correctness of the response. In the PA learning task, participants viewed the cue and its associated outcome simultaneously without receiving an overt response or corrective feedback. In both tasks, participants were trained across 150 trials. Learning was assessed in a subsequent test without a presentation of the outcome or corrective feedback. Results revealed an interesting disassociation in which ADHD participants performed as well as control participants in the PA task, but were impaired compared with the controls in the FB task. The learning curve during FB training differed between the two groups. Taken together, these results suggest that the ability to incrementally learn by feedback is selectively disrupted in ADHD participants. These results are discussed in relation to both the ADHD dopaminergic dysfunction model and recent findings implicating procedural learning impairments in those with ADHD.

1. Introduction

The ability to classify objects and events into distinct categories is important for human cognition. Our actions and decisions are based on categorization abilities that can either be based on a single past experience or be acquired in an incremental manner. A commonly used task to study categorization functions in cognitive neuroscience is the Weather Prediction Task (WPT), which is a typical probabilistic category learning task in which participants learn to classify multi-featured stimuli into one of two categories. This is typically done based on trial-by-trial corrective feedback. In the above-referenced WPT, participants predict an outcome, the weather, based on cues conveyed by a set of geometric features appearing on four individual cards presented in all possible combinations. An important aspect of the weather prediction task is its probabilistic nature. In particular, there is no one-to-one mapping between cues and outcomes. Declarative memorization is a less useful strategy in the weather prediction task because of the probabilistic relationship between cues and outcomes. Instead, the probabilities associated with particular cues and combinations of cues, acquired gradually across trials much as habits or skills are acquired, are most predictive of outcome. People with amnesia due to damage to the medial temporal lobe exhibit intact learning on the weather prediction task, although their declarative knowledge about the learning situation is impaired (Knowlton, Mangels, & Squire, 1996). By contrast, patients with basal ganglia

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disorders such as Parkinson's and Huntington's disease exhibit impaired learning in the weather prediction task (Knowlton, Squire, Paulsen, Swerdlow, & Swenson, 1996; Shohamy et al., 2004). This dissociation suggests the importance of the so-called procedural learning system (including basal ganglia) for probabilistic category learning.

Recent observations are advancing our understanding about how exactly the basal ganglia contribute to incremental learning (such as the kind employed in the WPT). The basal ganglia are paramount to procedural learning, enabling, among other things, the learning and mastering of task performance automatization. Dopaminergic neurons, arising from midbrain nuclei and innervating basal ganglia, have been consistently implicated in contributing to skill learning by mediating feedback processing and reward prediction (Fiorillo, Tobler, & Schultz, 2003; Hollerman & Schultz, 1998; Schultz, 1997; Schultz, Dayan, & Montague, 1997), features that are critical to trial-and-error learning (Shohamy, Myers, Kalanithi, & Gluck, 2008). In order to investigate whether the basal ganglia are critical for learning with feedback, Shohamy et al. (2004) devised two variants of the weather prediction task. A feedback-based (FB) task mirrored the typical weather prediction task. In this variant, participants initially guess the relationship between the probabilistic cues and the outcome and subsequently learn from experimenter-provided feedback about the correct outcome that is signaled by the probabilistic cues. This corrective feedback is eliminated in a paired associate (PA) variant of the weather prediction task. In this task, participants view a cue and its outcome simultaneously and learning proceeds through observation. Thus, in the PA version of the weather prediction task no response is required, except to press a key to advance to the next trial. These two variants of the weather prediction task share the common objective of learning outcomes signaled by a set of probabilistic cues. They differ in whether learning takes place by feedback (FB task) or by observation (PA task). Human functional neuroimaging (fMRI) studies corroborate findings in animals, showing that the WPT instigates basal ganglia response, and does so to a greater extent during feedback-based training than through mere observation devoid of feedback (Poldrack et al., 2001). Similarly, patients suffering from loss of dopaminergic innervation of the basal ganglia (e.g., Parkinson's disease) exhibit impaired learning when trained under feedback-dependent tasks (Knowlton et al., 1996), while maintaining intact performance via observational training (Shohamy et al., 2004; Smith & McDowall, 2006). A recent study offers direct evidence of the significance of midbrain dopamine to feedback-based learning in the WPT. Specifically, using positron emission tomography (PET), Wilkinson et al. (2014) demonstrated dopamine release in the right ventral striatum of healthy participants when performing the WPT based on trial-by-trial feedback, but not in an observational task with no feedback. These findings that patients with Parkinson's and Huntington's disease are impaired in the FB variant of the WPT, but not in the PA variant (Holl, Wilkinson, Tabrizi, Painold, & Jahanshahi, 2012; Shohamy et al., 2004), together with the findings on the involvement of the basal ganglia and striatal DA in the FB variant (Poldrack et al., 2001; Wilkinson et al., 2014), suggest that another population associated with dopaminergic deficiency might also demonstrate this interesting disassociation: the ADHD population.

1.1. ADHD and related deficiencies

Attention deficit disorder is one of the most common neurodevelopmental disorders with a prevalence of 3–5% of the general population. It is characterized by age-inappropriate levels of sustained attention, or impulse control, and activity levels that are present across multiple environments (American Psychiatric Association, 1994). ADHD typically surfaces early in childhood, and more often than not persists throughout adolescence and into adulthood (Barkley & Lombroso, 2000). Those affected by ADHD often exhibit significant educational, emotional, and social developmental deficits (Loe & Feldman, 2007; Wehmeier, Schacht, & Barkley, 2010).

Despite decades of research, the source of the neurocognitive dysfunctions and causes of ADHD are still hotly debated (Johnson, Wiersema, & Kuntsi, 2009). It has been suggested that individuals with ADHD suffer from executive function impairments (but see Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), including set shifting (Boonstra, Kooij, Oosterlaan, Sergeant, & Buitelaar, 2010), planning (Kofman, Larson, & Mostofsky, 2008), working memory (Schweitzer et al., 2000), and inhibition impairments (Barkley, 1997). Indeed, participants with ADHD demonstrate deficits in a variety of inhibition tasks such as the Simon task (Mullane, Corkum, Klein, & McLaughlin, 2009), the continuous performance test (Losier, McGrath, & Klein, 1996), and the stop signal task (Nigg, 1999). Extant literature reveals that along with executive function deficits, motivational processes, and reward-related responses are likewise affected among individuals with ADHD (Aase & Sagvolden, 2006; Luman, Oosterlaan, & Sergeant, 2005; Sagvolden, Aase, Zeiner, & Berger, 1998; Scheres, Milham, Knutson, & Castellanos, 2007; Stark et al., 2011). In particular, it appears that children and adolescents with ADHD are more sensitive to rewards than non-ADHD controls (Fosco, Hawk, Rosch, & Bubnik, 2015; Luman, van Meel, Oosterlaan, & Geurts, 2012), and prefer small immediate rewards to larger delayed rewards (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Demurie, Roeyers, Baeyens, & Sonuga-Barke, 2012; Tripp & Alsop, 2001).

In an attempt to account for the diverse range of deficits associated with ADHD, and in particular the motivational and cognitive impairments, a neurocomputational model was recently suggested by Frank and his colleagues (Frank, 2004; Frank, Santamaria, O'Reilly, & Willcutt, 2007; Maia & Frank, 2011). Their assumption is that striatal dopamine (DA) reduction in ADHD is the common source of both motivational (reinforcement) and cognitive deficits, observed in those with ADHD. In particular, Frank et al. (2007) stated that some of the ADHD cognitive dysfunctions may arise from dysfunctions of both the prefrontal cortex and the dopaminergic dysfunction within the basal ganglia. In support of this model Frank and his colleagues demonstrated that participants with ADHD are impaired in positive (Go) and negative (NoGo) reinforcement learning. Significantly, they found that medications improved Go reinforcement learning relative to NoGo reinforcement learning and that they were predictive of an improvement in the working memory of ADHD individuals in distracting conditions. This finding suggests the presence of common DA mechanisms in ADHD and supports a unified account of the DA function in ADHD.

In addition to the dysfunctions detailed above, procedural learning impairments have been shown to play a role in ADHD. Procedural learning ("how-to knowledge") is related to our ability to acquire skills, habits, and procedures. It is conceived as implicit as it occurs without intention or conscious awareness (Nissen & Bullemer, 1987) and is believed to be free of attentional resources (Frensch, Lin, & Buchner, 1998). Procedural knowledge is difficult to verbalize and is acquired in an incremental manner (Ashby & Casale, 2003). It has been shown that individuals with ADHD exhibit impaired performance in a variety of motor and cognitive procedural learning tasks such as motor sequence tapping (Adi-Japha, Fox, & Karni, 2011; Fox, Adi-Japha, & Karni, 2014, 2016; Fox, Karni, & Adi-Japha, 2016), serial reaction time (Barnes, Howard, Howard, Kenealy, & Vaidya, 2010; Prehn-Kristensen et al., 2011), probabilistic selection (Frank, Santamaria, O'Reilly, & Willcutt, 2007), visual category learning (Huang-Pollock, Maddox, & Tam, 2014), and artificial grammar learning (Laasonen et al., 2014; Rosas et al., 2010). ADHD impairments are evident not only during online skill