Developmental dyslexia is characterized by inaccurate and dysfluent reading. Although individuals with dyslexia most consistently demonstrate difficulties with storing, retrieving, and/or manipulating phonological representations (Brady et al., 1983; Shankweiler et al., 1979; Snowling, 2000; Stanovich & Siegel, 1994; Vellutino et al., 1994), a range of non-linguistic deficits in the motor and perceptual domains have also been reported for this population (for reviews see Folia et al., 2008; Lum et al., 2013; Nicolson & Fawcett, 2019; West et al., 2021). Multiple theories have been developed to explain the neurocognitive underpinnings of dyslexia. One hypothesis proposes that dyslexia is caused by deficits in implicit learning, which is critically involved in extracting and learning the sequential or distributional regularities in language (e.g., Nicolson & Fawcett, 2007, 2011; Ullman, 2004; Ullman & Pierpont, 2005). Implicit learning refers to the acquisition of knowledge without conscious awareness or intention and is thought to rely on the procedural memory system (or “knowing how”) Berry et al., 1993; Christiansen, 2019; Perruchet & Pacton, 2006; Shanks, 2005). In contrast to declarative memory, referring to conscious memory for facts and events (or “knowing that”), procedural memory refers to the learning of skills, rules, or patterned regularities in stimuli without awareness (Cohen & Squire, 1980). The implicit learning deficit hypothesis is supported by the high rates of comorbidity of dyslexia with other disorders (Boada et al., 2012; Ramus, 2003; Wimmer et al., 1999), suggesting a broad deficit in learning that extends beyond the language system. In the current study, we tested for the presence of domain-general implicit deficits in developmental dyslexia in adults.

*Skill learning* is a form of implicit learning that involves the acquisition of motor skills through practice and feedback and relies on the procedural memory system (e.g., Nicolson & Fawcett, 2007, 2011; Ullman, 2004; Ullman & Pierpont, 2005). Tasks such as serial reaction time (SRT), mirror tracing, and rotary pursuit are often used to measure skill learning. These tasks involve explicit feedback to guide performance but do not rely on prior knowledge or conscious awareness of the skill being learned. In support of the neural dissociation of the procedural memory system from the declarative system, amnesic patients with severe impairments in declarative memory show intact skill learning but impaired declarative memory for the episodes during which they learned the skills (Cohen & Squire, 1980). Research with neurological patient groups has suggested that different forms of skill learning have different neural substrates. For example, rotary pursuit is dependent on the basal ganglia (Gabrieli et al., 1997; Heindel et al., 1989) and mirror tracing is dependent on the cerebellum (Laforce Jr & Doyon, 2001).

*Statistical learning* *(SL)* is another form of implicit learning that plays a fundamental role in the perception and categorization of environmental inputs. Learners are thought to automatically extract the co-occurring patterns of exemplars embedded in sensory input mostly through passive exposure. Modern theoretical frameworks often introduce SL as a broad construct that encompasses a range of incidental learning paradigms (Bogaerts et al., 2020; Conway, 2020; Frost et al., 2019; Thiessen, 2017), including category learning, artificial grammar learning, and embedded pattern learning. However, the relative contributions of declarative and procedural memory to most SL tasks are largely unknown (Conway, 2020; Frost et al., 2015). There are mixed findings with a few patients with memory disorders that may reflect either variation in SL paradigms, patient abilities, or both (Cerreta et al., 2018; Covington et al., 2018; Schapiro et al., 2014). Neuroimaging findings have revealed both basal ganglia involvement (Karuza et al., 2013; McNealy et al., 2006; Willingham et al., 2002; see Conway & Pisoni, 2008 for a review) and the hippocampus (Schapiro et al., 2012; Tang et al., 2022; Wammes et al., 2022) across in SL tasks.

There are multiple reports of both intact and impaired implicit learning in dyslexia. Regarding skill learning, the most common paradigm used with individuals with dyslexia is a serial reaction time (SRT). SRT is a spatio-motor skill learning task in which participants typically see four horizontal spatial locations on a monitor and are instructed to press the corresponding button (from among four horizontal buttons) as quickly as possible. In some blocks, the order of stimulus locations follows a sequential pattern; in others, stimulus locations are presented randomly. Amnesic patients show normal learning of the repeating stimulus sequence as evidenced by faster reaction times (Nissen & Bullemer, 1987) and typical participants can exhibit skill learning for the repeated sequence without declarative memory for the sequence, although those typical participants who do develop declarative memory for the sequence show greater learning (Willingham et al., 1989).

A meta-analysis indicates that there appears to be a deficit in SRT learning in dyslexia (Lum et al., 2013; West et al., 2021). It is difficult to synthesize findings across studies, however, because sequences vary in their attentional demands and susceptibility to the development of declarative memory, both of which can influence learning (Cohen et al., 1990; Willingham et al., 1989) and may invoke cognitive processes beyond procedural memory. Further, there is some evidence that the SRT deficit is more pronounced in a task involving letters compared to a task involving nonlinguistic visual stimuli, suggesting that spatio-motor sequence learning in dyslexic individuals might be constrained by separate underlying learning systems (Gabay et al., 2012).

Mirror tracing and rotary pursuit are considered more pure measures of procedural memory, but are were less studied in the context of dyslexia. The specificity of mirror tracing and rotary pursuit tasks for the procedural skill-learning system has been demonstrated through multiple studies of patients with severe impairments in declarative memory. These patients had injuries to medial temporal-lobe or diencephalic brain regions. For example, the amnesic patient H.M. demonstrated intact learning skills for mirror tracing across days (Milner, 1962) and a year (Gabrieli et al., 1993) and for rotary pursuit (Corkin, 1968), but impaired declarative memory for the episodes during which he had learned the skills. Similar intact skill learning was shown by memory-impaired patients with Alzheimer’s disease on the same two tasks (Gabrieli et al., 1993a; Heindel et al., 1989). Mirror tracing has been examined only once in children with dyslexia, who were slower in performance but demonstrated typical learning across trials (Vicari et al., 2005). Rotary pursuit has not been examined in dyslexia.

Because spoken and written language inputs are rich in regularities, SL has been proposed as an important mechanism underlying typical language and reading development (Arciuli, 2018; Aslin & Newport, 2008; Erickson & Thiessen, 2015; Romberg & Saffran, 2010; Sawi & Rueckl, 2019). Empirical evidence ties SL with reading skills in both first and second languages (Arciuli & Simpson, 2012; Frost et al., 2013; Qi et al., 2019; Spencer et al., 2015; Tong et al., 2019). In typically reading adults and children, reading skills were more strongly associated with auditory SL than with visual SL (Qi et al., 2019). In children, the relationship between auditory SL and reading skills was further mediated by an emergent literacy skill: phonological awareness. Implicit auditory sequence learning might therefore constitute an early step towards phonological awareness, a pivotal building block of literacy development.

There have been mixed findings of deficits in SL in individuals with dyslexia. In the visual modality, some studies reported similar learning patterns between dyslexic and typically reading individuals (Howard Jr et al., 2006; Nigro et al., 2016; Singh et al., 2018; van Witteloostuijn et al., 2021), while others have reported impaired SL learning in dyslexia (Sigurdardottir et al., 2017; Tong et al., 2019) In the auditory modality, however, findings are more consistent, especially in adult participants: Across both linguistic and nonlinguistic stimuli, dyslexic adults have less success in recognizing embedded auditory patterns (Dobó et al., 2021; Gabay et al., 2015; Singh & Conway, 2021, p. 202). The lack of consensus in the literature regarding the status of SL in dyslexia is consistent with the pluralist view of SL (Frost et al., 2019) positing that SL across modalities and domains operates through partially overlapping, but distinct mechanisms. Therefore, a direct comparison between auditory and visual SL tasks of similar design is necessary to reconcile whether certain types of SL are indeed more vulnerable than others in dyslexia.

The present study had two major aims. First, we asked whether adults with dyslexia would show intact or impaired procedural memory on two motor skill learning tasks that have been well established as reflecting purely procedural memory: mirror tracing and rotary pursuit. Intact learning in dyslexia would contradict the idea that there is a broad impairment of procedural memory in dyslexia. Second, given that reading development is built upon inputs from both the visual and auditory sensory modalities, we asked whether statistical learning in these domains is correlated with reading skill. We used a classic embedded-pattern learning paradigm (Saffran et al., 1996) to define and measure SL performance for the following reasons. First, we aimed to compare our findings with decades of empirical proof that typical adults are capable of robust SL across sensory modalities (e.g., visual shape and color sequences: Turk-Browne et al., 2008; auditory tones: Saffran et al., 1999; speech syllables: Saffran et al., 1996; see Frost et al., 2015 for a review on the domain-generality vs. modality-specificity debate). Second, successful embedded-pattern learning does not require explicit knowledge of the task goal or any motor engagement (Batterink et al., 2015; Song et al., 2007), which enabled us to test for a domain-general procedural deficit across SL and procedural learning tasks.