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Research article

Motor competence is related to acquisition of error-based but not reinforcement learning in children ages 6 to 12

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ABSTRACT

Background: An essential component of childhood development is increasing motor competence. Poor motor learning is often thought to underlie impaired motor competence, but this link is unclear in previous studies.

Aims: Our aim was to test the relationship between motor competence and motor learning in the acquisition phase. Both reinforcement learning (RL) and error-based learning (EBL) were tested. We hypothesized that slower RL and slower EBL acquisition rates would relate to lower motor competence.

Methods and procedures: Eighty-six participants ages 6–12 performed a target throwing task under RL and EBL conditions. The Movement Assessment Battery for Children – 2nd edition (MABC-2) provided a measure of motor competence. We assessed EBL and RL acquisition rates, baseline variability, and baseline bias from the throwing task.

Outcomes and results: In a multiple linear regression model, baseline variability ($\beta = -0.49$, $p = <0.001$) and the EBL acquisition rate ($\beta = -0.24$, $p = 0.018$) significantly explained the MABC-2 score. Participants with higher baseline variability and slower EBL acquisition had lower motor competence scores. The RL acquisition rate was independent of MABC-2 score suggesting that RL may be less of a contributor to poor motor competence.

Conclusions and implications: Children with slower EBL acquisition had lower motor competence scores but RL acquisition was unrelated to the level of motor competence. Emphasizing the unrelated reinforcement mechanisms over error-based mechanisms during motor skill interventions may help children with poor motor competence better acquire new motor skills.

What this paper adds

An essential component of childhood development is increasing competence in motor skills. Poor motor competence (MC) negatively impacts other domains such as cognitive and social-emotional development. It is often hypothesized that poor motor competence may be a consequence of disordered motor learning. This study used a dimensional approach to test this hypothesis in the acquisition

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phase of reinforcement learning (RL) and error-based learning (EBL). Children ages 6 to 12 performed beanbag throws under RL and EBL conditions. The EBL acquisition rate predicted MC, such that children with slower EBL acquisition had lower MC scores. Additionally, baseline variability in throwing error predicted MC, such that children with greater baseline variability had lower MC scores. These results suggest that poor MC in childhood could arise independently from greater “noise” in the sensorimotor system and slower EBL acquisition. We found the RL acquisition rate did not relate to MC in our sample suggesting that RL may be less of a contributor to poor MC. These results could inform potential strategies for motor skill interventions in children who struggle with motor skills.

1. Introduction

An essential component of childhood development is increasing competence in motor skills [1–4]. Motor competence (MC) refers to the level of proficiency in all forms of goal-directed movements requiring coordination and control of the human body [5]. MC facilitates opportunities to interact with objects and other people that, in turn, drive physical, social, and cognitive development [4,6–9]. Impaired MC leads to less opportunities to practice emerging skills in multiple behavioral domains, which in turn disrupts the developmental trajectory [10,11]. For children with low MC, reading skills, educational achievement, emotional regulation, social development, cognitive development, and quality of life can be profoundly affected [3,12,13]. Children with poor MC are known to have poor cardiorespiratory fitness [14], lower bone density [15], and social and emotional issues [16]. Furthermore, many children with low MC have a low perception of their abilities and avoid participation in physical activities [17,18]. Although notably, some children have divergent levels of actual and perceived MC (e.g., low actual MC but high perceived MC) [19]. Furthermore, some children with low levels of actual and perceived MC still achieve high levels of participation in sports which suggests that other factors (such as socioeconomic status and parental support) also influence a child’s participation levels [20].

Poor MC is often thought to be a consequence of impaired motor learning [21–23]. The link between poor MC and impaired learning is most often studied in children with Developmental Coordination Disorder (DCD). DCD is defined as the acquisition and execution of motor skills below what is expected for the child’s age that is not better explained by another condition and interferes with daily life in domains such as self-care, play, and scholastic achievement [24]. Prevalence estimates vary with 5–6% commonly reported but the disorder is thought to be widely under-recognized and under-diagnosed [25,26]. Studies on the link between MC in DCD and motor learning are often underpowered and find conflicting empirical results [27]. The conflicting experimental results may stem, in part, from the fact that motor learning is complex and multi-dimensional.

Motor learning is a sustained change in the ability to execute a skilled movement. There are multiple models of motor learning [28] but we have elected to focus on the three stages of motor learning without describing the attentional demands on the learner. Those stages are acquisition, consolidation, and retrieval [29]. Acquisition is the encoding of motor memory associations between goal-directed movements and their outcome that the learner creates during practice [29]. Consolidation is the off-line, time-dependent stabilization of motor memory representations. Retrieval involves accessing stored motor memories when performing the task at a later time. This study is limited to the acquisition phase.

The learning process is driven by error feedback generated by goal-directed movements or the outcome of those movements. Motor learning is generally divided into two or more types of learning. First, reinforcement learning (RL), also called reward-based or exploratory learning, occurs when an association is created between the movement and the resultant reward [30]. The reward could be tangible (i.e. monetary) or intangible (i.e. successful outcome of the movement, praise). Movements that lead to success become more frequent or *reinforced*. Movements that lead to failure become less frequent. RL is driven by *reward prediction error*, the difference between the expected and the actual reward associated with an action [31]. The basal ganglia play key roles in the control, initiation, and sequencing of movement and are essential for reinforcement learning. For these reasons, basal ganglia dysfunction is a suspected contributor to impaired motor competence; although the evidence is mixed [22,32]. Second, error-based learning (EBL), also known as adaptation, modifies a movement pattern based on a perturbation [33]. EBL is driven by *sensory prediction errors*, the difference between the expected and the actual sensory consequences of a movement [34]. These errors provide the learner with a clear corrective signal [35]. The processing of sensory prediction errors in the cerebellum is critical for updating internal models which are neural representations of object dynamics that are used to plan movements and predict outcomes [35,36]. Cerebellar dysfunction is a suspected mechanism of impairments in both motor learning and motor competence in children with DCD and other common neurodevelopmental disorders [22]. Cerebellar structural and functional abnormalities have been found in children with DCD [37–39]. Gill et al. found strong positive correlations between cerebellar grey matter volume and MABC-2 scores in children with DCD linking cerebellar structure with motor competence (2022).

It is important to note that both RL and EBL processes are active when learning motor skills. No motor task purely isolates a single motor learning mechanism, but experimental paradigms are designed to create conditions where successful acquisition is highly dependent on a particular learning pathway [30]. For example, RL studies often use balance [40], reaching trajectories [41,42], or other tasks [43,44] where a clear corrective sensory feedback signal is unavailable and the learner must use reward prediction error to guide their exploration of motor solutions. EBL studies often use prisms [45], visuomotor rotation [46], force fields [47], or split belt treadmills [48] to create conditions where the learner must adapt to a perturbation using sensory prediction errors.

Previous reports evaluating the link between impaired motor learning and MC vary in the type and phases of learning studied, and in their empirical results. Differences in their results could stem from methodological differences in the motor task, difficulty level, sample size, or severity of motor impairment [27,43]. Among studies that investigated motor learning in children with DCD, some found that motor learning was impaired [40,43,46,49–51], while others found no evidence of a motor learning deficit [52–56]. Of importance, existing studies exclusively use a categorical approach where the distribution of a standard motor score is divided by a cut-off score to categorize participants into a DCD group or typically developing control group. Categorization is clinically important in the care of neurodevelopmental disorders and often controls access to services (i.e., healthcare, school services), but categorization collapses much of the variance in the distribution of a behavior, like MC, that is continuously distributed in the population. In the current study, we apply a dimensional approach where MC was viewed as a continuous variable to characterize the relationship between MC and acquisition across the full distribution.

Building on previous literature, the purpose of this study was to explicitly test the relationship between MC and motor learning using a throwing task paradigm in school-aged children. We focused here on the acquisition phase to determine if the ability to encode motor memory associations during practice underlies the relationship between MC and motor learning. We used the same participants and the same target throwing task under both RL and EBL conditions. Using the same task allowed us to hold certain methodological considerations (difficulty level, physical requirements of the task, sample criteria) constant while investigating the relative influence of the RL and EBL pathways. We hypothesized that slower RL and slower EBL acquisition rates would relate to poor MC, consistent with the assumption that impairment in one or more types and phases of motor learning contributes to developmentally poor MC. We also examined the influence of bias and variability because those are important parameters of accuracy that could confound the relationships between the acquisition variables and MC. Knowing the relationship between acquisition and MC has implications for effective motor skill intervention strategies and future research directions.

2. Methods

2.1. Participants

We used non-probabilistic convenience sampling to recruit 6 to 12-year-old children. We recruited through social media advertising, an outpatient occupational therapy clinic, and word-of-mouth. These ages were chosen because: 1) motor skills are expected to progress as more mature, adult-like motor control emerges during this period (i.e. motor imagery [57] and feedforward control [58]), 2) any major developmental disorders are likely recognized by this time, and 3) we expected that even the youngest participants would be able to follow the motor task directions and tolerate a ∼2-h lab visit. The recruitment goal was to sample participants across the continuum of typical and atypical development to facilitate a continuous approach rather than a categorical approach (see below section 2.5). The participating children could be typically developing or have diagnoses of Developmental Coordination Disorder (DCD), Attention-Deficit/Hyperactivity Disorder (ADHD), or Autism Spectrum Disorder (ASD). These neurodevelopmental diagnoses were part of the inclusion criteria because of their high incidence and close association with impaired MC [59–61]. Participants with injuries or other activity limiting conditions or whose primary language was not English were excluded. Caregivers provided written informed consent and participants provided their verbal assent. The participant's medical history and demographic data were obtained from the caregiver. This included the area deprivation index, a ranked metric of neighborhood socioeconomic disadvantage ranging from 1 to 100 with 100 being the most disadvantaged neighborhoods nationwide [62]. Families were paid $50 per participant and participants were allowed to pick a small toy at the end of the lab visit. The research protocol was approved by the Washington University Human Research Protection Office (IRB #:202201076) and conformed to the principles of the Declaration of Helsinki.

2.2. Motor task

Participants and a caregiver came to the lab where the participants performed a beanbag throwing task under two conditions, a reinforcement learning condition (RL) and an error-based learning condition (EBL). A coin flip was used to randomize which throwing condition would be performed first. Both conditions used the same floor target. The target was a gold disk of radius 8 cm which was placed at the center of a 2 m square white carpet. The center of the target defined the origin of the X and Y target dimensions. The throw line was 3 m from the target (Fig. 1). The white carpet was used to facilitate automated scoring with a camera that was mounted on the

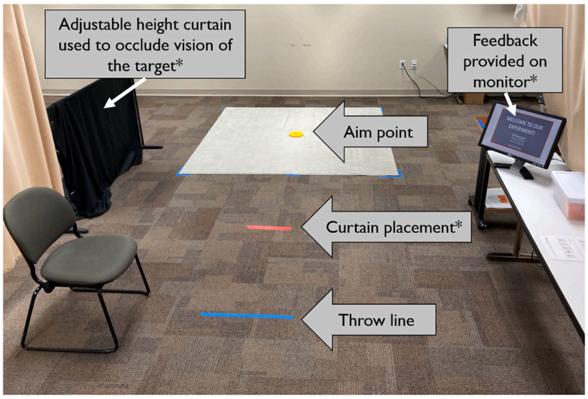

Fig. 1. Image of experimental setup. For the RL condition, the black adjustable height curtain was placed between the thrower and the target as indicated and the computer monitor was then placed on the floor immediately in front of the curtain to ensure easy visibility. * = applies only to the reinforcement learning condition.

ceiling above the target and provided an image of each throw to a custom Matlab program (R2022a, Mathworks Natick, MA). The program determined the position of the beanbag in the X and Y dimensions. Both tasks used the same 4-inch cotton beanbags, and all trials were completed with the dominant hand. Hand dominance was determined by participant-report and confirmed with a writing sample. The beanbags were either handed to the participant by a study team member or placed next to the participant on a chair. There was a delay of a few seconds between each trial while the previous trial was scored and the target was reset. Participants were required to use underhand throws for all trials.

For the RL condition, beanbags were thrown over a curtain that occluded the participant's view of the target, similar to Grand et al. [44]. While vision of the target was occluded, participants still had access to a view of the surrounding area and their somatosensory feedback from the throw. The curtain was placed 1 m from the throw line and the height of the curtain was adjusted for each participant so that it was just high enough to occlude a view of the entire target space. Participants were instructed to throw the beanbags as close to the target as possible. Hits and misses were determined using the Y-axis error where $y = 0$ was the center of the target (see Fig. 2A). Trials with Y-axis error within ±25 cm were defined as Hits. Trials with Y-axis error outside this range were Misses. The ±25 cm threshold was chosen based on pilot testing of the task, as a distance that would be achievable but challenging. Hit and Miss feedback was provided graphically on a computer monitor for 4 s after each trial. The computer monitor was placed on the floor immediately next to the curtain. Following a Miss, the monitor graphically displayed if the throw was *Too Far* (greater than 25 cm Y-axis error) or *Too Short* (less than −25 cm Y-axis error) for 4 s. The RL condition was designed to emphasize RL mechanisms as it limited the sensory feedback available to the participant and required greater motor exploration to achieve success. We determined that extra information would be necessary for the pediatric participants after piloting the RL conditions with adults. The adults were unable to reliably improve their performance on the task without directional feedback. Therefore, directional feedback was given (too far/too short) to reduce the space of possible motor solutions and facilitate acquisition of the skill over a relatively short practice session. The participants were still deprived of visual input and exploration was required to solve the motor problem (i.e. throw shorter or farther than the previous trial).

All of the feedback images were reviewed prior to the task to confirm that the participant understood the information provided. Before starting, we confirmed that the participant understood the correct strategy and how to use the directional feedback. Participants were prompted to answer the following questions:

> Question: If you throw too short, what should you do on the next throw?
>
> Correct Answer: e.g., Throw harder/farther
>
> Question: If you throw too far, what should you do on the next throw?
>
> Correct Answer: e.g., Throw lighter/ shorter

In the few instances where participants did not offer the correct answer, they were coached through the correct strategy prior to starting. Participants complete 4 blocks of 25 trials with short breaks of 1–2 min were given between blocks. Participants were instructed to try and hit the gold target but were not informed that the Y-axis was the only relevant scoring dimension. If the participant performed the RL condition first, they completed 5–10 unscored, unperturbed familiarization throws before the curtain was positioned to block their view. If the participant performed the EBL condition first, familiarization throws were unnecessary.

For the EBL condition, a prism adaptation task was used [45]. The prism goggles were standard chemical goggles with 30 diopter Fresnel press-on prisms applied to the lens (3 M Maplewood, MN). Adult and child size googles were available to accommodate the wide range of head sizes. The 30 diopter prisms created a shift of the visual field to the right. At 3.07 m the distance to the target, the prism goggles created a 92 cm horizontal displacement. Before donning the prisms, participants completed 25 baseline trials without any visuomotor perturbation. Then they donned the prism goggles and threw 50 trials. Lastly, participants completed 25 post-adaptation trials without the prism goggles.

2.3. Standardized assessments

We assessed MC as our outcome variable, and measured hyperactivity, autistic traits, and intelligence quotient to characterize the sample. Questionnaires were electronically delivered to caregivers using REDCap data capture tools [63]. Direct assessments were administered prior to or following the throwing tasks.

2.3.1. Motor competence (MC)

The Movement Assessment Battery for Children – 2nd edition (MABC-2) provided an objective measure of MC and coordination for use as the outcome variable in our analysis [64]. The MABC-2 is norm-referenced functional skill test commonly used to establish risk or presence of DCD in school-age children [3,26,49,51,65,66]. The MABC-2 has eight test items covering 3 domains: manual dexterity, aiming and catching, and balance. In the same age range as the current sample, the MABC-2 correlates with the Bruininks-Oseretsky Test of Motor Proficiency (BOT-2) at $\rho = 0.90$ and has a Cronbach's alpha of 0.90 [67]. The total standard score provides an overall score of MC across the 3 tested domains and was used in our analysis. Total standard scores range from 1 to 19 (mean = 10, sd = 3) and account for participant age. Scores below the 5th percentile are indicative of server motor difficulty. Scores from the 6th to the 15th percentile suggest minor difficulties and careful monitoring is suggested. Scores above the 15th percentile indicate no motor difficulty. When considering the high end of MC, some MABC test items have been found to exhibit ceiling effects [68,69].

Note that the MABC-2 contains an aiming and catching test item requiring 10 bean bag tosses. That test item was distinct from our motor learning task (a larger beanbag thrown unperturbed at a shorter distance). All of the MABC-2 test items were performed consecutively either before or after the motor learning task. We performed a secondary analysis to ensure that this test item did not create a relationship between the motor task acquisition rates and the MABC-2 score (see section 2.5).

2.3.2. Hyperactivity

To quantify caregiver-reported hyperactivity, we used the Hyperactivity/Impulsivity content scale raw score which is a subtest from the Conners-3 Parents' Rating Scale [70]. The Conners-3 is a behavioral rating scale for identifying ADHD in children and adolescents and includes questions related to cognitive, behavioral, and emotional symptoms. The Hyperactivity/Impulsivity content scale score range from 0 to 42 with mean scores in a typically-developing population ranging from 6 to 9, and scores greater than ~20 (depending on age and sex) indicating hyperactivity. This content scale has a test-retest reliability of 0.77–0.83 [71].

2.3.3. Autistic traits

We assessed autistic traits with the Social Responsiveness Scale (SRS-2) School Age, a metric of deficits in reciprocal social behavior. The SRS indexes quantitative autistic traits across the entire population, including individuals with and without ASD [72], and differentiates individuals with ASD at a level of 3 standard deviations above the mean. The SRS-2 has a Cronbach's alpha of ≥0.92 at all ages [73]. We extracted the SRS T-score for the analysis. T-scores can range from 32 to 114 (mean = 50, sd = 10). Scores of ≤59 are indicative of typical development while T-scores >59 are consistent with risk or diagnosis of ASD.

2.3.4. Intelligence

Intelligence was assessed with the Kaufman Brief Intelligence Test (KBIT-2) [74]. The KBIT-2 provides verbal, non-verbal, and composite intelligence scores. We used the IQ composite score which ranges from 40 to 160 (mean = 100, sd = 10). Scores below 75 are indicative of intellectual disability. The KBIT-2 has a test-retest correlation of r = 0.88 in children ages 4–12 and correlates with the Wechsler Intelligence Scale for Children-4th edition at r = 0.77 in children ages 6–16 [75].

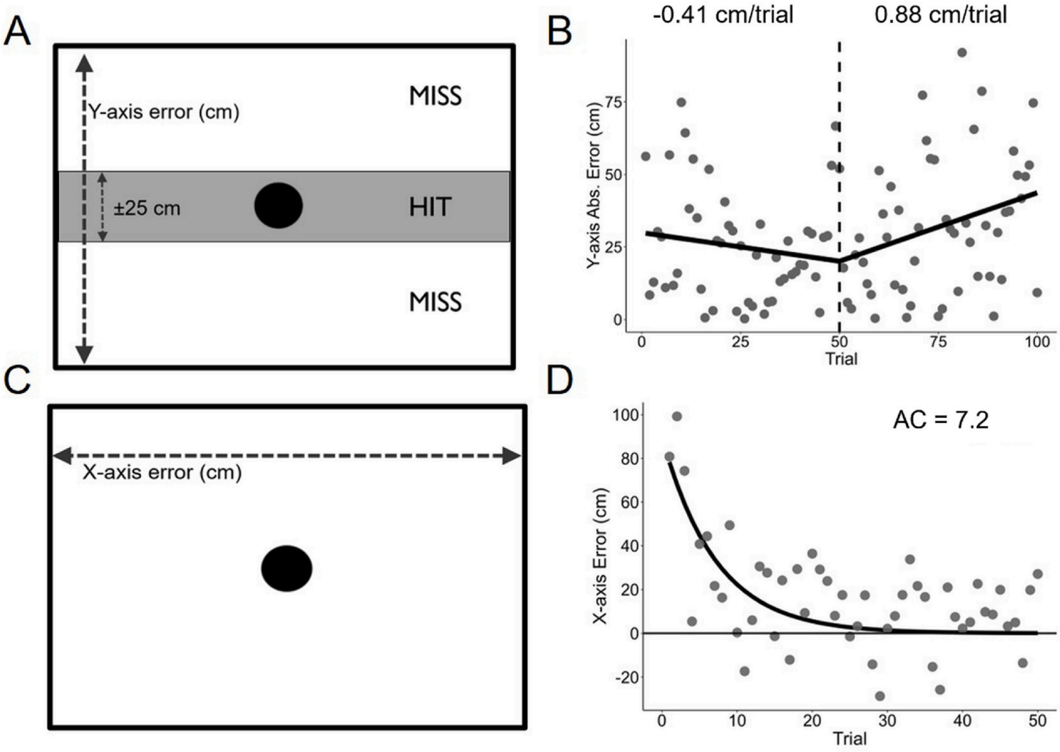

Fig. 2. Target scheme and data extraction from RL and EBL throwing tasks. A. In the RL task, Hit and Miss were defined by the Y-axis error. The Y-axis origin was at the center of the target and throws landing within ±25 cm were Hits. B. Individual participant data from the RL task, showing the absolute value of the Y-axis error and a fitted spline model with a knot at 50 trials. The slope for trials 1–50 was extracted as the acquisition rate. For this participant the slope for trials 1–50 was −0.41 cm/trial. The slopes from trials 51–100 not used to quantify RL acquisition. This participant 51–100 slope was 0.88 cm/trial. C. In the EBL task, the signed X-axis error was of interest due to the rightward visual displacement created by the prisms. D. Individual participant data from the EBL task, showing a fitted exponential decay function. Note the large initial error due to the prism. This participants adaptation coefficient was 7.2.

2.4. Motor task variables

The main metric extracted from the RL condition was the absolute value, Y-axis error of each trial (Fig. 2A). Both bias (i.e. constant error) and variability (i.e. precision) may change across trials during a target task [76,77]. Some throwers may improve on the task by reducing bias whereas others may reduce their variability. Thus, it is parsimonious to look at a measure of accuracy, which is sensitive to changes in bias and variability. Additionally, because success in the RL task was defined on the Y-axis only, we focused on Y-axis absolute error as our primary outcome, rather than utilizing two-dimensional measures of accuracy such as radial error [78], which would confound the task-relevant and task-irrelevant dimensions. Trials landing closer to the center of the Hit zone ($Y = 0$) correspond to smaller absolute value Y-axis errors and the slope of that error quantifies how accuracy changed across trials with negative slopes representing improvement on the task. Observation of the participants during data collection and visual inspection of the data revealed that accuracy tended to improve and then worsen across the 100 trials. Fatigue and loss of motivation, interest, or focus may have influenced performance after approximately 50 trials. To quantify the RL acquisition rate, we used a linear spline mixed regression model with the absolute value Y-axis error as the outcome and a knot set at 50 trials. The model used a random intercept and random slopes for trials 1–50. A fixed effect slope was used for trials 51–100 as a random slope did not improve model fit. The modeling from a representative participant is plotted in Fig. 2B. The spline model results confirmed that error decreased over trials 1–50 and increased for trials 51–100. The fixed effect for trials 51–100 was +1.35, which indicated that, on average, the slope increased (error increased) in the second half of the RL trials for all participants. To avoid the effects of repeated trials, we operationally defined the RL acquisition rate as the slope from trials 1–50. A negative slope indicated that the participant acquired the RL task. The more negative (lower) the slope, the faster the RL acquisition rate.

The main metric extracted from the EBL task was the X-axis error (Fig. 2C). In the EBL condition, the prisms created a systematic visual field shift to the right, and we were most interested in how participants would adapt to this bias. As such, we focused on constant error as a measure of bias. Additionally, because the visual field distortion was in the X-axis, it was most parsimonious to model constant error on the X-axis only. To quantify the EBL acquisition rate, we extracted the adaptation coefficient (AC) by fitting an exponential decay function ($y = A + B * e^{-t/AC}$) [45]. The modeling from a representative participant is plotted in Fig. 2D. The adaptation coefficient reflects the number of trials needed to adapt two-thirds of the way to their asymptote. All AC values are positive numbers and lower AC values indicate faster acquisition (i.e. faster adaptation to the prisms). For example, an AC value of 15 indicates that the participant needed 15 trials to complete two-thirds of their adaptation.

Additionally, the 25 baseline, unperturbed trials from the EBL condition were used to determine the participants' baseline bias and baseline variability. Baseline bias was calculated as the mean error. Baseline variability was calculated as the SD about the mean error [77].

2.5. Statistical analysis

All statistical analyses were performed in the R environment version 4.2.2 (R Core Team, 2022). Descriptive statistics were calculated for the sample characteristics and assessment scores. A *t*-test was used to compare MABC-2 standard scores of boys and girls. To check that the acquisition variables reflected acquisition of the motor skill, one-sample t-tests were used to determine if the mean RL slope was less than 0 and the mean EBL AC value was less than 50. In our primary analysis, we determined if RL and EBL acquisition rates relate to MC using a multiple linear regression model where the MABC-2 standard score was explained by the RL slope and EBL AC. We hypothesized that both slower RL acquisition and slower EBL acquisition would relate to lower MC. This would be confirmed in the regression model by a significant negative coefficient with RL slope and a significant negative coefficient with EBL AC. Baseline bias and baseline variability were included as covariates to control for these pre-intervention performance characteristics. Since motor variability is known to be elevated in children with poor MC [79], adding it to the regression model allowed us to examine the relationship between acquisition rate and MC score with the influence of variability removed. Additionally, Pearson correlations were used to quantify the bivariate relationships among the model's explanatory variables and with the MABC-2 score. As part of a sensitivity analysis, the SRS-2 score, Conners-3 hyperactivity/impulsivity sub-score, and the KBIT-2 score were added as covariates to determine the influence of autistic symptoms, hyperactivity, or gross intelligence on the relationship between motor learning and MC.

We performed a secondary multiple linear regression analysis because the aiming & catching component of the MABC-2 has a throwing item that requires an underhand beanbag throw to a floor target or a tennis ball throw to a wall target, depending on age. To ensure that this aiming & catching score did not drive relationships with MC we repeated the multiple regression model with the aiming & catching component removed. Instead, a composite score of the other two MABC-2 domains (balance and manual dexterity) was used as the outcome variable.

For all regression models, we performed regression diagnostics to check for linear relationships, homoscedasticity, and independent normally distributed errors. Additionally, we checked for dependence among the predictors (i.e., multicollinearity). Statistical significance was defined as $\alpha = 0.05$ for all models.

3. Results

We enrolled a total of 88 participants. Two participants did not have a sufficient number of trials due to behavioral issues during the motor task and were excluded from the analysis. Of the 86 participants with complete data, 4 were reported to have ASD, and 9 were reported to have ADHD, with 1 having both diagnoses. Demographic information and descriptive assessment scores are displayed in Table 1. The sample was enriched with participants with lower MC, as evidenced by 32 participants with MABC-2 total percentile scores below 15 (indicates the presence or risk of DCD) [80]. There was no difference in the MABC-2 standard score between boys and girls ($t = -0.327$, $p = 0.745$). Our sample provided a suitably large range of MC scores (Fig. 3A) and the motor task variables (Fig. 3B–E), which facilitated the use of a dimensional approach that treats MC as a continuous variable rather than a categorical variable.

Fig. 3B and C shows that all participants successfully acquired both motor tasks. Acquisition of the RL task is indicated by the distribution of the slopes. All RL slopes fell below zero signifying the participants decreased their error across trials and a one-sample *t*-test confirmed that the mean slope falls below zero ($t = -24.9$, $p < 0.001$). Acquisition of the EBL task is indicated by the distribution of AC values, all of which fall below 50 signifying that all participants completed two-thirds of their adaptation to the prisms within the 50 trials. A *t*-test confirmed that the mean AC value falls below 50 ($t = -39.9$, $p < 0.0001$).

A multiple linear regression analysis was appropriate for these data. There was no evidence of multicollinearity with all of the variance inflation factor values less than or equal to 1.36. There was no evidence of heteroscedasticity (Breusch Pagan Test $bp = 0.568$, $p = 0.967$), and residuals were normally distributed (Shapiro Wilk Test $w = 0.978$, $p = 0.166$) with a mean of zero. The MABC total standard score was normally distributed (Shapiro Wilk Test $w = 0.982$, $p = 0.295$).

The results from the primary regression analysis are shown in Table 2. The overall multiple linear regression model was statistically significant ($F(4,81) = 10.66$, $p = <0.001$) and explained 31.2 % of the variance in MABC-2 standard score. The baseline variability ($\beta = -0.49$, $p = <0.001$) and the EBL AC ($\beta = -0.24$, $p = <0.018$) significantly explained the MABC-2 standard score, while the RL slope and baseline bias were not statistically significant. Surprisingly, the RL slope coefficient value, while non-significant, had a positive value, which runs counter to the hypothesized relationship. Both baseline variance and EBL AC had a negative relationship with MABC-2 standard score indicating that as baseline variability increases (more variable throwing) and EBL AC increases (slower acquisition), MC decreases. The RL and EBL acquisition rates did not meaningfully correlate with each other ($r = 0.07$, $p = 0.54$) nor with baseline variability (RL: $r = 0.05$, $p = 0.68$; EBL: $r = 0.16$, $p = 0.14$). The bivariate relationships between each of the predictor variables and the MABC-2 standard score are visualized in Fig. 4A–D.

In our secondary analysis, we repeated the multiple linear regression model with the aiming and catching component removed

Table 1
Descriptive characteristics of the sample. All values are mean (sd) followed by the range except those that are percentage (count).

	N = 86
Demographics	
Age (years)	9.49 (1.97)
	6.0–12.99
Sex: Male	58.1 % (50)
Female	41.9 % (36)
Race: Black or African-American	8.1 % (7)
White	88.4 % (76)
Asian	3.5 % (3)
Ethnicity: Hispanic, Latino	9.3 % (8)
Area Deprivation Index[a]	35.7 (17.5)
	7.0–94.0
Motor Competence	
MABC-2 Total Percentile[b]	28.31 (25.5)
	0.1–99.0
MABC-2 Total Standard Score[b]	7.59 (3.06)
	1–17
Hyperactivity	
Conners: Hyperactivity/Impulsivity[c]	8.07 (7.49)
	0.00–34.00
Autistic Traits	
SRS T-score[d]	43.97 (7.41)
	34.2–73.1
Intelligence	
KBIT Composite Score[e]	112.62 (13.57)
	83.0–141.0

[a] The Area Deprivation Index uses US Census tract data to estimate the relative deprivation in an area. Higher values represent greater socio-economic deprivation and lower values represent less deprivation.

[b] MABC-2 scores are in percentile or standard scores that range from 1 to 19 (mean = 10, sd = 3). Lower scores represent lower motor competence.

[c] Conners-3 Hyperactivity/Impulsivity scores is a subtest of the Conners-3 and ranges in score from 0 to 42 (mean scores range from 6 to 9). Higher scores represent greater hyperactivity.

[d] SRS-2 T-scores range from 32 to 114 (mean = 50, sd = 10) with scores higher than 59 indicating risk or diagnosis of ASD.

[e] The KBIT-2 composite IQ score ranges from 40 to 160 (mean = 100, sd = 10). Scores below 75 are indicative of intellectual disability.

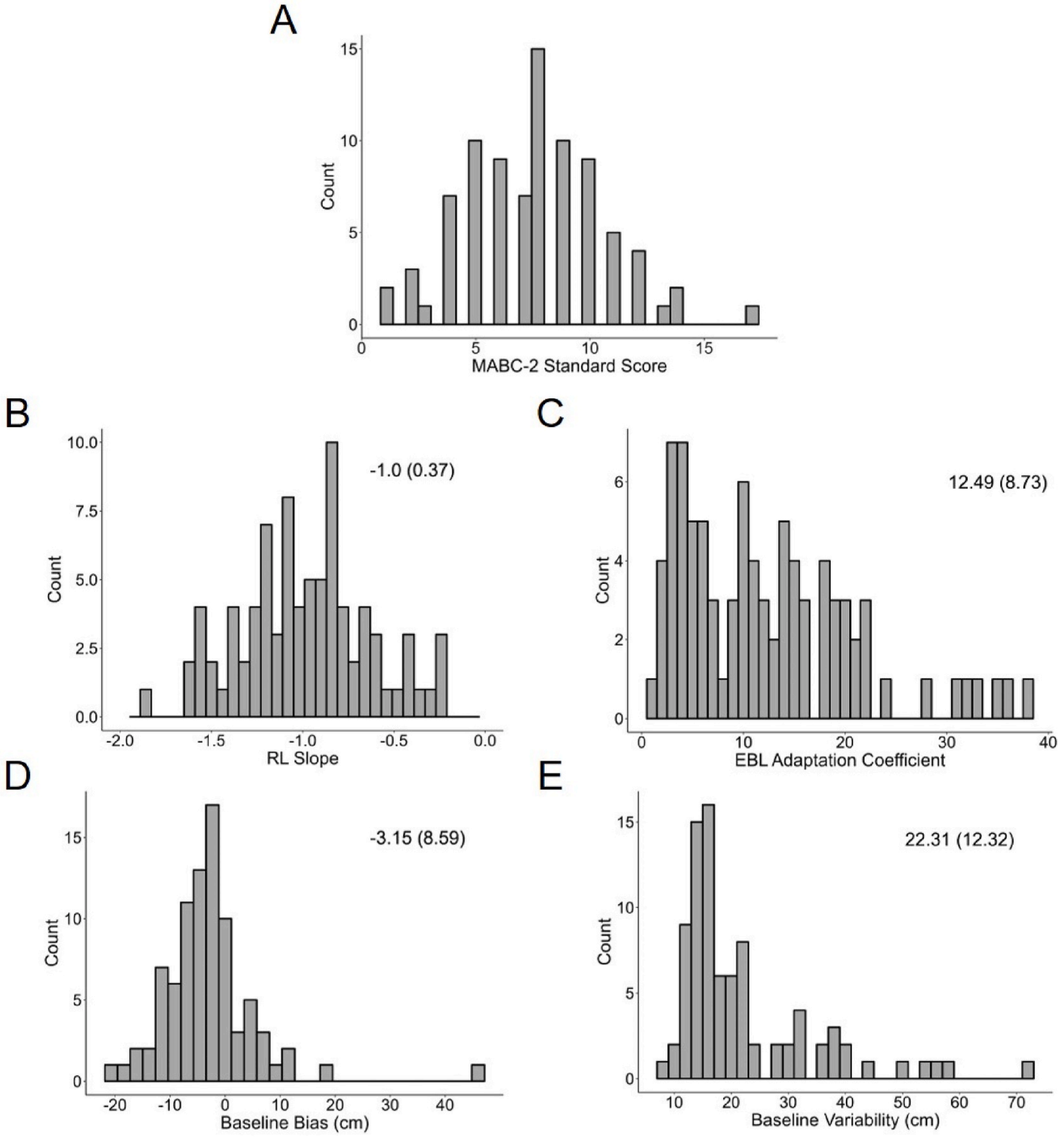

Fig. 3. Distributions of the model variables. RL = Reinforcement learning. EBL = Error-based learning. In B – E mean (sd) is shown on panel.

Table 2

Results of the primary multiple linear regression model using the MABC-2 standard score as the outcome. EBL = Error-based learning. AC = adaptation coefficient quantifying the EBL acquisition rate. RL = Reinforcement learning. CI = 95 % confidence interval.

Variable	Estimate	Standard Beta	CI	Standardized CI	P-value
Intercept	12.84	0.0	10.81–14.88	−0.18 – 0.18	**<0.001**
EBL AC	−0.08	−0.24	−0.15–−0.02	−0.44–−0.04	**0.018**
RL Slope	1.41	0.17	−0.07 – 2.89	−0.01 – 0.35	0.062
Baseline Variability	−0.13	−0.49	−0.18–−0.07	−0.69–−0.29	**<0.001**
Baseline Bias	0.03	0.09	−0.04 – 0.11	−0.12 – 0.30	0.394

from the outcome. The significant coefficients and their confidence intervals were nearly identical to the original model (See Supplementary Table 1) indicating that the throwing test item was not driving the relationship between EBL AC and MABC-2 standard score.

As part of our sensitivity analysis, the SRS-2 T-score, the Conners-3 hyperactivity/impulsivity content scale raw score, and the KBIT-2 total IQ score were tested as predictors by adding them to the primary model. This was done in a step-wise fashion, adding each individually and then in combination. None of those tested models improved the model fit as measured by the corrected Akaike

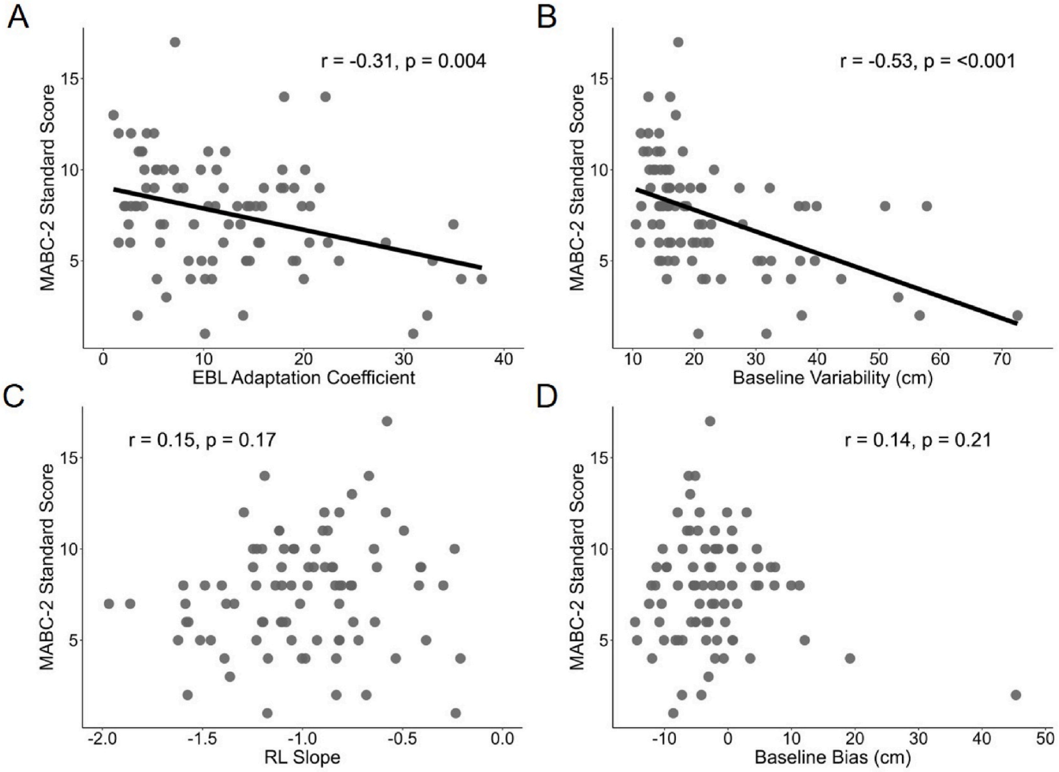

Fig. 4. Bivariate Pearson correlations between predictors and MABC-2 standard score. Correlation coefficient and p-value are shown on each panel. Black lines are linear fit for the significant relationships only.

Information Criterion.

4. Discussion

This is the first report to concurrently test RL and EBL acquisition within the same participants, facilitating comparison of the relations each type of learning has with MC. The dimensional approach with a larger sample than much of the prior literature enhanced our ability to quantify the relationships each type of learning had with a standard metric of MC. Slower EBL acquisition related to poor MC, partially confirming our hypothesis. Consistent with previous reports, we also found that higher baseline variability had a negative relationship with MC. Children with higher variability had lower MC. RL acquisition was trivially related to MC (standardized beta = 0.12 and not statistically significant) which suggests that RL mechanisms do not meaningfully contribute to MC in children.

Children who adapted more slowly to the visual displacement created by the prisms had lower MC scores. This is consistent with the notion that disordered motor learning contributes to poor MC. Similar reports found impaired visuomotor adaptation in children with low MC [50,51]. It is noteworthy that the acquisition rate on one discrete, error-based throwing condition related to a score of MC that covers multiple motor domains. EBL is an important and ubiquitous part of our daily activities that is intimately related to motor control. For example, the internal models and sensory prediction errors that drive real-time motor control in daily activities also drive EBL [81,82]. The relationship between our discrete target throwing task and overall MC may reflect this importance.

Contrary to our hypothesis, the RL acquisition rate did not have a significant negative relationship with MC, suggesting that the RL pathway is not contributing to impaired MC. There may be several reasons for this result. As we have previously discussed, a major neural substrate of EBL is the cerebellum, which is often implicated in neurodevelopmental motor issues, while RL is more dependent on the basal ganglia. Our result may suggest that the cerebellum is the more important neural substrate underlying associations between motor learning and motor competence. It may also be that the relationship between RL and MC was obfuscated by the signal-to-noise ratio of the outcome we chose to operationalize RL learning. Our focus was on the rate of acquisition as measured by the change in the target error in the RL task, but other measures that capture trial-and-error RL mechanisms may be better able to detect a link between RL and MC. For example, future studies could explore changes in the biomechanical parameters (e.g., kinematics, kinetics) of the behavior. Finally, we did provide the learner with coarse directional feedback (too short/too far) to make the task easy enough that improvement could be detected during the single session. This coarse directional feedback may have created some overlap between the RL and EBL conditions, but there was still no statistical relationship with MC. The lack of relationship between RL and MC found here is consistent with previous RL studies that found no learning deficit in children with low MC [52,53].

Baseline variability, which is often used to quantify sensorimotor noise, was moderately and negatively related to MC indicating that children with higher baseline variability had lower MC. This finding is consistent with previous studies showing that children with low MC have high levels of sensorimotor noise [79]. We note that the associations between MC, EBL, and baseline variability are consistent with the presentation of cerebellar dysfunction [56,82]. Cerebellar dysfunction is known to exert a significant developmental impact, including low MC [37,83]. The cerebellum exerts control over the sequence, force, and timing of coordinated movements [56] and has a crucial role in EBL, as it determines the sensory prediction error by comparing the predicted outcome of a motor command with the sensory feedback and corrects for the discrepancy [82]. We cannot speculate beyond that since we did not collect data about brain structure or function in the current study. The absence of a relationship between MC and RL learning acquisition is consistent with the notion of cerebellar dysfunction as these learning pathways are largely independent. For example, adults with cerebellar degeneration can still learn via reinforcement mechanisms despite observations that they are unable to learn via error-based mechanisms [84].

Importantly, the relationship between error-based skill acquisition and MABC-2 score was found after controlling for sensorimotor noise. This allowed us to determine that the relationship between error-based acquisition and motor competence was not confounded by high levels of sensorimotor noise which could impair performance on both the error-based learning task and the MABC-2 test items and create a spurious relationship between the two.

The focus of this study was on the initial acquisition of motor skills that occurs during practice. It is possible that the relationship between acquisition rate and MC differs from the relationship between retention testing and MC [85–87]. Regardless of whether performance in the retention test is impaired in children with poor MC, impaired acquisition has important consequences on its own on short and longer time scales. On short time scales, children with slow EBL acquisition rates may not gain enough skill in an allotted practice time (e.g., duration of a physical education class or physical education unit). On longer time scales, slow EBL acquisition rates could lead to larger MC lags with peers, and impact activity choices along with adjacent social-emotional or cognitive development. Future research should continue to test multiple motor learning pathways and incorporate the retention phase and longer time scales. These motor learning pathways should also be tested for generalizability relative to development in other, non-motor domains that entail ongoing skill acquisition (e.g., social and cognitive domains).

It is crucial to provide motor rehabilitation clinicians and educational professionals with foundational knowledge about motor learning so that they can optimize therapeutic interventions. Our study design, by examining relationships between motor learning and motor competence across a continuous range of behavior rather than focusing on impairment, could inform interventions and educational approaches that enhance all children's development along the dimension of motor competence. This approach facilitates a view of motor competence that is not based on categories or cut-off scores but on improving a child's position along that dimension. It may be that children above a given cut-off score would also garner salient developmental benefits from motor skill interventions. For children with frank clinical impairment, effective motor skill interventions could improve their motor competence and reduce the secondary effects that occur in areas such as social-emotional development, metabolic health, and quality of life [88]. Since RL acquisition was independent of MC, one option suggested by our data would be to emphasize those independent reinforcement mechanisms during motor skill interventions to help children with poor motor competence maximize their acquisition of the practiced motor skill. Alternatively, some children might benefit from interventions to improve their EBL abilities, however, this assumes EBL mechanisms are malleable and can be improved with practice. The efficacy of both of these suggested motor intervention options would need to be assessed with rigorous study.

4.1. *Limitations*

First, our recruitment strategy was primarily based on social media advertising and word-of-mouth. Our non-probability convenience recruitment strategy may have led to parents self-selecting for concerns related to motor function. Our sample was enriched for families with concerns about a child's motor skills, as indicated by 37 % with MABC-2 scores <15th percentile, although most did not have a developmental diagnosis. While the sample size was adequate, it will be important to test generalizability by replicating in other samples, including ones with greater racial/ethnic diversity. Second, medical history was provided by caregiver report only and was not verified. It is possible that other unreported comorbid conditions could have influenced the results. Third, the MABC-2 may have difficulty distinguishing between high scoring performers which may have lowered the variance on that dimension in our sample. Given that our sample is enriched for low coordination participants and that our MABC-2 standard score was normally distributed, the impact of the MABC-2's ceiling effect on our results was likely minimal. Furthermore, the MABC-2 score is composited from three domains each with a number of discrete tasks. We acknowledge that poor performance on one domain could be offset by excellent performance in another which may mischaracterize the child's true level of impairment [89]. While covering a broad range of motor skills, it is also possible that the MABC-2 misses other key motor skills that are developmentally important and incompletely characterizes the participants level of motor competence. Finally, the difficulty of the RL condition may have limited the range of slopes with most participants having only small negative slopes. This may have limited our ability to detect a relationship between MC and RL mechanisms.

5. Conclusions

In this sample of school-age children, those with lower MC were slower to acquire a motor skill under EBL conditions and had increased variability when executing a target throwing task. RL acquisition was independent of MC which may suggest that, for children with poor motor competence, the RL pathway could be emphasized during motor skill interventions to optimize acquisition of the practiced motor skill. We speculate that improving EBL mechanisms with training could also lead to improvements in MC.

However, further study is needed to assess the extent to which EBL mechanisms can be modified with interventions. Future research should continue to test dual learning mechanisms in order to compare their relative contributions to the outcome of interest, especially in children with lower motor competence. Future research should also extend the time course of motor learning to assess relationships between motor skill retention and MC.

Ethical approval

This study was approved by the Washington University Human Research Protection Office (IRB #:202201076) and conformed to the Declaration of Helsinki. Caregivers provided written informed consent and participants provided verbal assent.

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Data availability statement

The authors are willing to provide the data upon request.

CRediT authorship contribution statement

Jeffrey D. Konrad: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Natasha Marrus:** Writing – review & editing, Conceptualization. **Keith R. Lohse:** Writing – review & editing, Formal analysis, Conceptualization. **Kayla M. Thuet:** Writing – review & editing, Investigation. **Catherine E. Lang:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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