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Performance-based and questionnaire measures of executive function in adolescents with type 1 diabetes

Emily R. Hamburger[1] · Morgan Lyttle[1] · Bruce E. Compas[2] · Sarah S. Jaser[1]

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Abstract The purpose of the current study was to examine executive function (EF) in adolescents with type 1 diabetes using both performance-based and questionnaire measures in relation to diabetes indicators. Adolescents age 13–17 completed performance-based measures of EF and measures of adherence. Adolescents' parents reported on adolescents' EF and adherence. HbA1c and frequency of blood glucose monitoring (glucometer data) were obtained from adolescents' medical records. None of the performance-based measures of EF were significantly associated with adherence or with HbA1c. Parent-reported problems with EF were associated with poorer adherence, and adolescents who scored in the impaired range of the Behavioral Regulation Index of EF had significantly poorer adherence (both parent-reported adherence and frequency of blood glucose monitoring) and higher HbA1c than those in the normal range. Our findings suggest that parent-reported measures of EF may be more strongly linked to diabetes indicators than performance-based measures.

Keywords Adherence · Adolescents · Executive function · Diabetes management · Type 1 diabetes mellitus

✉ Sarah S. Jaser
sarah.jaser@vumc.org

1 Department of Pediatrics, Vanderbilt University Medical Center, 2525 West End Ave., Suite 1200, Nashville, TN 37232, USA

2 Department of Psychology and Human Development, Vanderbilt University, Nashville, TN, USA

Introduction

During adolescence, youth with type 1 diabetes (T1D) become increasingly responsible for their own diabetes management. The tasks of diabetes management are complex and demanding, including checking and interpreting blood glucose levels, calculating insulin dosage, and remembering to carry supplies (American Diabetes Association, 2018). As youth transition from diabetes care that is largely parent-directed to independent care, the cognitive demands of these tasks increase. Executive function (EF), or the set of skills necessary to plan and initiate action, organize materials, regulate impulses, and shift attention, plays a large role in the ability to effectively carry out these tasks. However, EF is still developing during adolescence, and therefore, the responsibility for treatment management may be mismatched with adolescents' cognitive abilities (Duke & Harris, 2014). What is not known is which specific areas of executive functioning are associated with critical diabetes self-management behaviors (e.g., blood glucose monitoring). Further, it has not been established whether performance-based measures of EF provide additional, valuable information in this population.

In a seminal paper, Miyake and colleagues (2000) theorized that three major EFs exist: shifting, updating, and inhibition. Shifting is the ability to disengage from less important tasks and engage in more relevant tasks. It is involved in the ability to switch focus, or to move between mental and physical operations. Updating is linked with working memory and is necessary for monitoring information and updating it as needed for a specific task. Inhibition is the ability to intentionally suppress or end responses or impulses that are no longer appropriate. Each of these factors of EF has the potential to influence aspects of diabetes management, but this has yet not been examined. On the other hand, Common EF, which is made up of the specific shifting, updating, and inhibition EF factors, and can be broadly understood to include the ability to actively maintain task goals and goal-related information (Miyake & Friedman, 2012), may be more strongly associated with diabetes indicators than specific EFs, as diabetes management involves a complex set of behaviors that likely require a combination of EFs (shifting, updating, and inhibiting). While several models of EF exist, the Miyake model is one of the most widely used models, and it served as the basis of the NIH Toolbox measures of EF (Gershon et al., 2013.

Although different assessment methods may capture different aspects of EF, performance-based measures have generally been considered the "gold standard" for measuring EF (Pennington & Ozonoff, 1996). However, the majority of studies examining EF in youth with T1D have used questionnaire measures of EF, most commonly, the parent-reported Behavior Rating Inventory of Executive Functioning (BRIEF). In a review of studies that examined associations between questionnaire measures of EF, adherence, and glycemic control in young people with T1D (Duke & Harris, 2014), all six studies found evidence of significant relationships between EF and adherence. However, only one study found a significant link between EF and glycemic control, and this study used a diabetes-specific measure of EF (Duke et al., 2014). One of the strongest of these studies, which followed 239 youth with T1D over 2 years, found that, although changes in global EF (reported by mothers) did not predict changes in adherence or glycemic control, improvements in behavioral regulation (which includes shifting, inhibition and emotional regulation) predicted better child-reported adherence over time (Miller et al., 2013). In a more recent study, adolescents' problems with EF (as reported by mothers) were associated with worse treatment adherence and worse glycemic control, and mothers' own problems with EF were associated with poorer diabetes management (Goethals et al., 2018). These findings support a growing body of evidence indicating that, among youth with T1D, parent-reported problems with EF, particularly behavioral regulation, are linked with poorer diabetes self-management.

To our knowledge, only one study has incorporated both questionnaire and performance-based measures of EF in youth with T1D. In a sample of high school seniors with T1D, questionnaire ratings, but not performance measures of EF, were found to be associated with adherence in adolescents with T1D. Further, although performance-based measures and questionnaires (mother reports) were both related to glycemic control, performance measures were not associated with glycemic control after controlling for IQ (Suchy et al., 2016). In a longitudinal follow-up of this sample, however, researchers found that lower scores on EF performance-based measures predicted greater declines in glycemic control over 2 years, and self-reported EF did not predict adherence or glycemic control over time (Berg et al., 2018). This study included a narrow age range (high school seniors) which may not generalize to younger adolescents, who are beginning the transition to more independent diabetes management. Further, these studies analyzed composite or global measures of EF, rather than focusing on different aspects of EF. Importantly, performance-based measures and questionnaire measures of EF may provide insight into different aspects of EF, as performance-based measures use highly controlled tasks with little room for interpretation, as opposed to the everyday activities that form the basis of questionnaire measures. Thus, more information is needed about how specific EFs may relate to indicators in adolescents with T1D.

Current study

We sought to extend the existing literature on EF in adolescents with T1D by examining EF using both performance-based and questionnaire measures in relation to diabetes indicators. We hypothesized that adolescents who had greater problems with EF would have poorer adherence to the diabetes treatment regimen and poorer glycemic control. Further, we hypothesized that performance-based measures would be more strongly linked with diabetes-related indicators, and would predict significant variance above and beyond parent-reported EF. We also conducted exploratory analyses to see whether specific aspects of EF (shifting, updating, and inhibition) were related to diabetes-related indicators.

Methods

Procedure

Adolescents and their parents were approached during regularly scheduled outpatient diabetes clinic visits at an academic medical center between October, 2015 and May, 2016. Adolescents were eligible for the study if they were between the ages of 13–17, diagnosed with T1D for at least 12 months, and had no other major health problems. Of the 92 families approached, 27 refused, yielding a participation rate of 71%. Data analyses included 65 adolescent–parent dyads.

All procedures were approved by the University's Institutional Review Board/Human Subjects Protection Program. After providing informed assent/consent, adolescents and their parents completed questionnaires in REDCap (Research Electronic Data Capture). Glucometers were downloaded if available and clinical data (HbA1c) were obtained as part of the regular clinic visit. Before the administration of performance measures, adolescents were asked to check their blood glucose levels. If the result was below 70 mg/dL, the teen would be instructed to treat their low with a quick acting sugar and wait 15 min. None of teens had a blood glucose level below 70, but two teens had blood glucose levels (73 and 84 mg/dL), which they chose to treat before testing. We did not place an upper limit on blood glucose level; however, one participant had a blood glucose level of 220 mg/dL and chose to bolus insulin before continuing with the study.

Testing was conducted in a private space within the clinic setting, which was kept as free from distractions as possible. Testing sessions typically lasted between 20 and 30 min, as measures included in this analysis were the only assessments administered during the session. The testing was conducted by research staff who were trained and supervised by a licensed clinical psychologist.

Measures

Demographic and clinical variables

Parents provided information on demographic variables, including adolescent sex, age, race/ethnicity, and family income. We also asked parents to report whether the adolescent had a diagnosis of Attention Deficit/Hyperactivity Disorder (ADHD). Clinical information, such as date of diagnosis and treatment type (e.g., insulin pump or injections) was obtained from the medical record.

Executive function

Updating/working memory

Teens were administered the Working Memory Index (WMI) from the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V) (Weschler, 2014). The WMI includes three subtests: Digit Span, Picture Span, and Letter Number Sequencing. During the Digit Span subtest, teens were asked to repeat strings of digits in a particular order (either the same order as they were originally given, in reverse order, or in numerical order). Picture Span required teens to view a page with one or more pictures and then select the picture(s) in sequential order from options on a response page. During Letter Number Sequencing, teens were read a list of letters and numbers and then asked to repeat the list with letters in alphabetical order and numbers in ascending order. Age-adjusted scores were used in the analysis, with higher scores representing better working memory. The average reliability coefficient for the WMI has been reported as 0.92 (Wechsler, 2014).

EF shifting

The Trail Making subtest (condition 4: number-letter switching) of the Delis–Kaplan Executive Function System is intended to measure the ability to shift mental sets (Delis et al., 2001). On this assessment, teens were asked to quickly draw connecting lines between letters and number in sequence. Trained RAs timed the teens on this task, and longer times indicated poorer ability to shift mental sets. For analysis, norm-based age-adjusted scaled scores were used. The test–retest reliability coefficient for the combined number + letter sequencing conditions on the Trail Making test is reported as 0.78 (Delis et al., 2001).

In addition, the Dimension Change Card Sort task from the National Institutes of Health (NIH) Toolbox (Gershon et al., 2013) was used to measure flexibility of thinking and attentional shifting. In this task, teens were asked to match pictures based on either shape or color depending on a cue word. Higher scores indicated greater accuracy and lower response time. Age-adjusted scaled scores were used for analyses. This task has been shown to exhibit excellent test–retest reliability, with an intraclass correlation coefficient of 0.92 for children aged 3–15 years (Weintraub et al., 2013).

EF inhibition

The Flanker Inhibitory Control and Attention Test from the NIH Toolbox (Gershon et al., 2013) was used to measure adolescents' ability to focus attention and inhibit responses to irrelevant stimuli. Teens were asked to quickly choose which direction a target arrow was pointing while ignoring arrows to either side. Higher scores represent faster response time and higher accuracy. Age-adjusted scaled scores were used for analyses. The Flanker task on the NIH Toolbox has been found to have excellent test–retest reliability, with an intraclass correlation coefficient of 0.95 for children aged 3–15 years (Weintraub et al., 2013).

Parent report questionnaire

The Behavior Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2000) was completed by parents to assess adolescents' cognitive abilities used in planning, manipulating attention, organization, and time management. The questionnaire consists of 86 items which comprise eight subscales (Initiate, Working Memory, Plan/Organize, Organization of Materials, Monitor, Shift, Inhibit, and Emotional Control), two indices (Metacognition and Behavioral Regulation), and one overall Global Executive Composite (GEC). Parents rated each item on a

3-point Likert scale, with 1 being "never a problem" and 3 being "often a problem," such that higher scores indicate worse EF. T scores are adjusted for age and sex, with a mean T score of 50 and SD of 10. Scores at or above 65 are considered to be clinically significant, and scores at or above 60 are considered moderately impaired. Given the small percentage of participants who scored above the clinical cutoff, we opted to use the cutoff for impairment in our analyses. The BRIEF also includes two validity scales: Negativity and Inconsistency. In our sample, only one parent was found to have an elevated Negativity score, and two parents had questionable Inconsistency scores. BRIEF data for the participant with the elevated Negativity score were excluded from analyses.

Adherence

Self-Care Inventory

Adolescents and parents completed the Self-Care Inventory (SCI), which measures adolescents' adherence to important aspects of the T1D treatment regimen, such as blood glucose monitoring, insulin administration, diet, and exercise (La Greca, 2004). Items are rated on a scale of 1 ("Never do it") to 5 ("Always do it as recommended without fail"), with higher scores representing better adherence. Using both self-report and parent-report reduces potential sources of bias. Cronbach's alpha was .80 for adolescents' self-report and .80 for parent report.

Blood glucose monitoring

Adolescents' glucometers were downloaded to determine frequency of blood glucose monitoring (average checks per day) over the previous 30 days. Blood glucose monitoring (BGM) is an objective measure of adherence that has been strongly linked with glycemic control (Guilfoyle et al., 2011). We were able to obtain complete BGM data for most ($n = 61$) of our sample. In cases where meter data were incomplete, participants were excluded from analyses involving BGM.

Glycemic control

Glycosylated hemoglobin (HbA1c) is an average of blood glucose levels over the previous 8–12 weeks. HbA1c was obtained as part of the regular clinic visit using the point-of-care Bayer Diagnostics DCA2000® Analyzer. The American Diabetes Association recommends HbA1c < 7.5% (58 mmol/mol) in adolescents with T1D.

Analysis plan

Statistical analyses were performed using IBM SPSS Version 25. We conducted descriptive analyses to characterize the sample. To test our hypothesis, that greater problems with EF would be related to worse diabetes indicators, we first conducted bivariate correlations to assess the associations between the performance-based and questionnaire measures of EF with adherence (parent and self-report on the SCI, BGM) and glycemic control (HbA1c). Similar to previous studies (e.g., Limbers & Young, 2015), we used the BRIEF subscales that correspond with Miyake's shifting (Shift), initiate (Inhibit and Initiate) and updating (Working Memory) factors for analyses. In addition, we examined differences in adherence and glycemic control by conducting nonparametric tests between adolescents who were above and below the clinical cutoff on measures of EF: *T* score above 60 on the BRIEF, scaled score < 85 on the WISC-V WMI and on the NIH Toolbox measures, scaled score < 7 on the DKEFs. Finally, we conducted multivariable linear regression analyses to determine whether EF was a significant predictor of glycemic control or adherence, adjusting for demographic (sex) and clinical (duration of diabetes, treatment type) factors. We then tested whether performance-based measures predicted significant variance in glycemic control or adherence, above and beyond the BRIEF measure, by entering the performance-based measures of EF in the final step of the regression model. With our sample size, we had sufficient power (.99) to detect large ($\boldsymbol{d} = .50$) effects, power of .81 to moderate effects ($\boldsymbol{d} = .30$), and we had power of .20 to detect small effects ($\boldsymbol{d} = .10$).

Results

Descriptive results

Mean age of adolescents in our sample was 15.1 ± 1.3, duration of diabetes was 5.8 ± 3.7 years, and 58.5% of adolescents were using insulin pumps. In the current sample, 47.7% were female, and 20.3% were of minority race/ethnicity. Adolescents had an average HbA1c of 8.9%, and only 11 (15.4%) were meeting the target for glycemic control (HbA1c < 7.5%), similar to national samples (Miller et al., 2015). Parents reported that 6 adolescents had a diagnosis of ADHD (9.5% of the sample), and 5 of 6 parents reported that their child was taking medication to treat ADHD. Mean scores on the performance-based measures of EF and on the BRIEF were in the average range. However, as seen in Table 1, a considerable number of adolescents scored in the mildly impaired range for

Table 1 Descriptive statistics for executive function measures

	Range	Mean (SD)	N (%) impaired
Performance-based measures			
WISC-V Working Memory Index (standard score)	82–146	107.02 (14.66)	4 (6.2)
DKEFS trails (scaled score)	1–12	7.52 (2.99)	21 (32.3)
NIH Flanker (age adjusted standard score)	80.02–118.79	101.76 (8.47)	3 (4.8)
NIH card sort (age adjusted standard score)	62.41–124.21	105.86 (10.86)	2 (3.2)
BRIEF T-scores (parent report)			
Global executive composite (GEC)	36–74	51.55 (9.53)	12 (18.8)
Behavioral Regulation Index (BRI)	37–72	47.95 (8.49)	8 (12.5)
Initiate	36–79	53.11 (10.63)	14 (21.9)
Inhibit	41–69	47.84 (7.56)	7 (10.9)
Shift	38–76	48.44 (9.63)	11 (17.2)
Working memory	38–87	55.64 (11.54)	27 (42.2)

WISC-V Weschler Intelligence Scale for Children, fifth edition, *DKEFS* Delis–Kaplan executive function system. Impaired scores for the performance-based measures are 1 Standard Deviation below the population mean. Impaired scores for the BRIEF scales are T scores > 60, indicating at least mild impairment

specific subscales, especially Initiate (21.5%) and Working Memory (41.5%). Diabetes duration and adolescent age were not significantly associated with any of the performance-based measures of EF or with scores on the BRIEF. Diabetes duration was related to significantly lower self-reported adherence ($r = -.44$, $p < .001$) and poorer glycemic control ($r = .35$, $p = .005$). Adolescent sex was significantly related to performance on the DKEFs Trail-making test ($t = 2.01$, $p = .048$), with girls performing worse than boys, but parents rated boys significantly higher than girls on the BRIEF GEC ($t = 2.51$, $p = .014$), Shift ($t = 2.91$, $p = .005$), and BRI ($t = 2.53$, $p = .014$).

Bivariate associations

As seen in Table 2, none of the performance-based measures of EF were significantly associated with adherence (P-SCI, A-SCI, or BGM) or with glycemic control (HbA1c). We found several significant associations between parent-reported EF on the BRIEF and diabetes indicators. Higher scores on the GEC scale, indicating greater problems with global EF, were associated with lower adherence per parent report ($r = -.28$). Higher scores on the Behavioral Regulation Index of the BRIEF were related to lower parent-reported adherence ($r = -.30$). Similarly, higher scores on the Shift subscale of the BRIEF were related to significantly lower parent-reported adherence ($r = -.29$), but the associations between the Working Memory, Initiate, and Inhibit subscales were not significant. None of the EF measures were related to glycemic control, the objective measure of adherence (BGM) or adolescents' self-reported adherence (A-SCI).

Group differences

We next conducted Mann–Whitney tests to determine whether there were differences in diabetes-related indicators between adolescents whose scores were above and below the clinical cutoff on the BRIEF ($T \geq 60$, indicating at least mild impairment). We found that adolescents who scored in the impaired range on the GEC had significantly lower parent-reported adherence on the SCI ($U = 103.00$, $Z = -2.757$, $p = .006$). There were no significant differences in glycemic control, BGM, or self-reported adherence.

In addition, we found that adolescents who scored in the impaired range on the BRI had significantly lower parent-reported adherence on the SCI ($U = 60.00$, $Z = -2.626$, $p = .009$), significantly higher HbA1c ($U = 122.5$, $Z = -2.063$, $p = .039$), and lower BGM ($U = 120.50$, $Z = -2.055$, $p = .040$). There were no significant differences in self-reported adherence.

Finally, we found that adolescents who scored in the impaired range on the Shift subscale had significantly lower parent-reported adherence on the SCI ($U = 50.00$, $Z = -3.487$, $p < .001$), and lower BGM ($U = 177.00$, $Z = -1.974$, $p = .048$). There were no significant differences in self-reported adherence or glycemic control. We did not observe any significant differences in diabetes-related indicators in association with the Working Memory, Initiate or Inhibit subscales.

For the performance-based measures of EF, there were no significant associations between scores in the clinical range and diabetes indicators for the DKEFs Trailmaking test or either of the NIH Toolbox measures, and the only significant association for the WISC-V WMI was with

Table 2 Correlations between executive function measures and diabetes outcomes

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. GEC	–														
2. BRI	.81***	–													
3. Working memory	.85***	.53***	–												
4. Initiate	.82***	.48***	.75***	–											
5. Inhibit	.68***	.82***	.42***	.33**	–										
6. Shift	.76***	.90***	.51***	.47***	.61***	–									
7. P-SCI	− .28*	− .30*	− .13	− .24	− .21	− .29*	–								
8. A-SCI	− .11	− .09	− .12	− .18	− .05	− .06	.36*	–							
9. Flanker NIH	.00	− .04	.02	− .02	.01	− .04	.18	.04	–						
10. Card sort NIH	.02	− .14	.06	.07	− .05	− .09	.17	− .07	.37**	–					
11. DKEFS trails	− .29*	− .11	− .37**	− .34**	− .01	− .10	.01	.14	.23	.15	–				
12. WISC WMI	− .35**	− .34**	− .30*	− .30*	− .17	− .42**	.20	.12	.11	− .03	.37**	–			
13. A1C	.12	.23	.07	.15	.15	.09	− .34*	− .37**	.15	.04	− .01	− .20	–		
14. Daily BGM	− .09	− .14	− .11	− .11	− .07	− .07	.21	.53***	.04	.17	.06	.07	− .45***	–	
15. Child age	− .19	− .13	− .19	− .14	− .24	− .02	− .16	− .08	.00	− .08	.12	.04	− .18	− .11	–

GEC global executive composite, *BRI* Behavioral Regulation Index, *P-SCI* parent-reported Self Care Inventory, *A-SCI* adolescent self-reported Self Care Inventory, *DKEFS* Delis–Kaplan executive function system, *WISC WMI* Weschler Intelligence Scale for Children, Working Memory Index, *Daily BGM* average daily blood glucose monitoring

*$p < .01$; **$p < .01$; ***$p < .001$

parent-reported adherence (U = 33.00, Z = − 2.15, $p = .030$), with parents of children who scored below the clinical cutoff reporting significantly lower adherence than those who scored above the cutoff.

Regression analyses

We conducted a series of linear regression analyses to determine whether executive function was a significant predictor of glycemic control (HbA1c) and adherence (BGM, P-SCI, A-SCI). In the first step of each model, we adjusted for diabetes duration, as it was associated with glycemic control and adherence. We also adjusted for treatment type (pump vs. injections) in the model, as the use of insulin pumps has been linked with better glycemic control. Finally, we adjusted for adolescent sex, since it was associated with some measures of executive function. To reduce the number of analyses, and to account for the high correlations between the different scales of the BRIEF, we chose to include the BRI scale from the BRIEF, as this index was most significantly associated with diabetes-related indicators in the earlier analyses. In the last step of the model, we added the DKEFs and WISC-V measures of EF. We chose not to include the NIH measures in the model, as they were not significantly associated with any of the other EF measures or diabetes indicators in our correlation analyses.

The overall model predicting HbA1c was significant (F (*6*, *53*) = 3.94, $p = .002$), accounting for 23% of the variance in glycemic control. In the final model, diabetes duration and BRI were significant predictors, but the performance-based measures of EF (DKEFs and WISC-V) were not significant (see Table 3). Similarly, the overall model predicting BGM, the objective measure of adherence, was significant (F (*6*, *53*) = 2.34, $p = .045$), accounting for 12% of the variance. In the final model, diabetes duration and treatment type (pump vs. injections) were significant predictors, but the BRI and performance-based measures of EF were not significant (see Table 3).

The overall model predicting A-SCI (adolescent self-reported adherence) was significant (F (*6*, *52*) = 4.32, $p = .001$), accounting for 26% of the variance in adherence. In the final model, diabetes duration and insulin pump use were significant predictors, but none of the measures of EF were significant. Finally, the overall model predicting P-SCI (parent-reported adherence) was not significant (F (*6*, *42*) = 1.24, $p = .305$). To determine if the order of entry was important, we also conducted the regression analyses with the same EF predictors entered in reverse order: the performance-based measures of EF were entered in step 2 and the BRI was in step 3. The results were essentially unchanged; BRI was the only significant predictor in the final model predicting A1C.

Discussion

The current study was one of the first to use both performance-based and questionnaire measures of EF in adolescents with T1D. Overall, the adolescents in our sample were within the normal range of functioning on parent-reported and performance-based measures of EF, despite

Table 3 Parent-reported and performance-based EF as predictors of diabetes-related outcomes

Predictor	HbA1c				BGM			
	R^2	ΔR^2	*β*	*F*	R^2	ΔR^2	*β*	*F*
Step 1	.20			4.77**	.19			3.69*
Diabetes duration			.36**				− .28*	
Child sex			.14				− .12	
Treatment type			.23				− .28*	
Step 2	.29	.08*		5.55**	.24	.05		3.36*
Diabetes duration			.35**				− .27*	
Child sex			.23				− .20	
Treatment type			.22				− .27*	
BRI			.30*				− .24	
Step 3	.30	.02		3.84**	.26	.02		2.56*
Diabetes duration			.34**				− .30*	
Child sex			.25				− .15	
Treatment type			.19				− .30*	
BRI			.27*				− .24	
DKEFS			.09				.17	
WISC WMI			− .14				− .12	

BRI Behavioral Regulation Index, *WISC WMI* Weschler Intelligence Scale for Children, Working Memory Index

*$p < .05$; **$p < .01$; ***$p < .001$

the fact that a minority (only 15.4%) were meeting targets for glycemic control. We observed that a significant percentage of our sample had parent-reported problems with Initiate and Working Memory, and there was subtle impairment on the DKEF measure of shifting. Although scores on the performance-based measures were not significantly linked with diabetes-related indicators, parent-reported EF was significantly associated with adolescents' adherence and glycemic control. As the BRIEF and P-SCI measures were both completed by the parent, it is possible that shared method variance may inflate these correlations. Additionally, parents completed these measures in clinic after learning their child's HbA1c results, which may have impacted their perception of their child's adherence behaviors and EF skills. Further, we did not find that specific aspects of EF were significantly associated with diabetes-related indicators; rather, global EF and behavioral regulation were most strongly linked with parent-reported and objective measures of adherence, as well as glycemic control. In our sample, none of the EF measures or diabetes indicators were significantly related to age, despite adolescents increasingly taking on responsibility for their management, as they grow older. It is possible that parents of younger adolescents in our sample provided help with diabetes management tasks and therefore compensated for EF deficits that would interfere with treatment if the child were solely responsible. As the adolescents become more independent in their treatment, these deficits may become more apparent.

Based on our findings, and in line with other studies (Bagner et al., 2007; Suchy et al., 2016), the behavioral/emotional aspect of EF seems to be the most salient for diabetes management. One of the strengths of our study was the inclusion of a more objective measure of adherence (BGM), and it is noteworthy that we found significant differences in frequency of BGM between adolescents who were and were not moderately impaired per parent report on the Behavioral Regulation Index. The BRI consists of the inhibit, shift, and emotional control scales, which may be particularly important in relation to diabetes management, which requires people to shift from stimulating tasks (e.g., talking to friends, playing video games) to perform diabetes tasks (e.g., monitoring blood glucose), and the ability to inhibit impulses, such as eating before checking blood glucose or calculating an insulin dose.

Contrary to our hypotheses, none of the performance-based measures of EF were related to any of the diabetes-related indicators assessed, but the WISC Working Memory Index was significantly correlated with 5 of 6 BRIEF scales, and the DKEFs was associated with 3 of 6 BRIEF scales. While these correlations were lower than anticipated, the results indicate that these performance measures were capturing some of the EF skills observed by parents. However, the NIH Toolbox measures did not correlate with any of the other performance-based measures or parent reports of EF, suggesting that these measures did not converge with other measures of EF in our sample. The parent-reported BRIEF may be more strongly linked to adherence than performance-based measures because it reflects behavior in real-life situations, which may map on more closely to diabetes-related tasks than performance-based measures completed in the lab. Performance-based measures are generally administered under strict guidelines by trained professionals, representing an ideal scenario where the tasks are designed to optimize performance, and little is left up to the individual's interpretation. In contrast, questionnaire measures inquire about how an individual typically performs in everyday situations where there are fewer explicit instructions about how to accomplish tasks (Toplak et al., 2013). It is possible that these differences between performance-based measures and parent-report questionnaire measures may represent different facets of EF, which may have unique relationships with diabetes indicators and adherence. Based on our findings, the BRIEF or other parent-reported measures of EF may serve as an initial screener for problems with EF (rather than beginning with a full neuropsychological assessment) in this population, though further investigation in larger samples is warranted (Compas et al., 2017).

Limitations

Several limitations to the study are important to note. First, our sample size was fairly small, which limited our ability to detect small effects, and results must be interpreted with a degree of caution. It is possible that the small effects observed in other studies (e.g., Suchy et al., 2016) were not detected in our study, due to our smaller sample size. In addition, we did not measure full-scale IQ, which could impact performance-based tests of EF. It is also worth noting that our measures of updating and working memory include both verbal and nonverbal tasks, yet the measures of shifting and inhibition include only nonverbal tasks, and therefore may be impacted by the participants' level of verbal proficiency. We also did not place an upper limit on blood glucose levels before testing. Although only one participant reported a high blood sugar level that they chose to treat, acute hyperglycemia has been shown to cause impairments in cognition (Sommerfield et al., 2004) and future studies may wish to more tightly control for this. Finally, we only included the parent-reported BRIEF, not the self-reported measure. We chose to use the parent report, as this has been more strongly associated with adherence in youth with T1D than self-reported EF (Miller et al., 2013; Suchy et al., 2016). Future studies may be served well by including factors that have been shown to impact EF, such as mood (Mitchell & Phillips, 2007) and sleep (Anderson et al., 2009). These factors may mediate the relationship between EF and diabetes indicators, as adolescents with diabetes are at risk for increased rates of depressive symptoms and sleep disturbances (Lawrence et al., 2006; Patel et al., 2018).

Clinical implications

Understanding the specific nature of EF deficits in relation to diabetes indicators is essential, as adolescents may benefit from the use of skill-specific strategies or accommodations (Wasserman et al., 2015). For example, the use of new diabetes devices and technology (insulin pumps, continuous glucose monitors) may be more difficult for people with EF deficits. Additionally, parents may benefit from psychoeducation on adolescent development and EF to provide realistic expectations and avoid giving over too much responsibility for treatment management too soon.

In our sample, the Behavioral Regulation Index was the EF index most strongly associated with adherence and glycemic control. These findings suggest that interventions targeting adolescents' coping with diabetes-related stress or emotion regulation may be beneficial (Jaser et al., 2016). Further, adolescents who have difficulty with inhibiting impulses and shifting attention may benefit from greater external structure, such as phone reminders for diabetes tasks or check-ins with a school nurse.

In conclusion, findings from the current study add to the growing body of literature on EF in youth with T1D. More research is still needed, including longitudinal studies. By gaining a greater understanding of which specific EF skills are most strongly associated with adherence to diabetes treatment, we may have the potential to intervene and break the negative cycle.

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Compliance with ethical standards

Conflict of interest Emily R. Hamburger, Morgan Lyttle, Bruce E. Compas and Sarah S. Jaser declare that they have no conflict of interest.

Human and animal rights and informed consent All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study. This article does not contain any studies with animals performed by any of the authors.

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