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ORIGINAL ARTICLE

Child-Caregiver Interactions During a Collaborative Motor Task in Children with Cerebral Palsy: A Descriptive Exploratory Study

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Abstract
Caregiver support is an important contextual factor in the daily functioning of children with cerebral palsy (CP), but few studies have examined child-caregiver interactions during collaborative motor tasks to identify characteristics of effective support that should be promoted in clinical interventions. The aims of this exploratory study were to (1) describe the interaction dynamics of children with CP and typically developing (TD) children with their respective caregivers during a collaborative motor task and (2) develop clinically relevant hypotheses regarding features of child-caregiver interactions that relate to effective caregiver support. Twelve child-caregiver dyads (6 including children with CP, 6 including TD children) participated. Each dyad attempted to construct the tallest tower structure in 10 min using marshmallows and raw spaghetti. Time-series of upper extremity positions were obtained through motion capture and used to examine child-caregiver movement coordination. Videos were coded for language structure and number of building materials used. Five TD dyads and one CP dyad successfully constructed a free-standing tower. During periods of increased tower breakage, TD dyads demonstrated increased movement coordination compared to CP dyads. Unsuccessful dyads (most of whom were CP dyads) demonstrated interaction dynamics characterized by the child leading in movement during periods of increased tower breakage. Overall, in TD dyads, caregivers used more interrogatives than imperatives, and children used more imperatives than interrogatives. This pattern was reversed for CP dyads. From these results we identified future hypotheses about aspects of interactions that may facilitate collaborative motor performance (and thus caregiver support) between children with CP and their caregivers.

Keywords Cerebral palsy · Caregivers · Interaction · Physical therapy · Occupational therapy · Contextual factors

Introduction

Children with cerebral palsy (CP) experience multiple body structure and body function impairments along with associated activity limitations and participation restrictions (Østensjø et al., 2004). Body structure and body function impairments have been well-addressed in physical and occupational therapy for many years (Anaby et al., 2017). With the introduction of the International Classification of Functioning, Disability and Health (ICF; World Health Organization, 2001), therapy interventions now place increased emphasis on activities and participation. The ICF also acknowledges the influence of contextual factors (i.e., personal and environmental factors) on an individual's functional independence (Rosenbaum & Stewart, 2004). These contextual factors are thought to perhaps be the greatest causes of chronic illness and disability (Baum & Fisher, 2014; Davidson, 2015; Nicholls, 2018), but clinical practice rarely includes systematic assessments of contextual factors on a child's functioning and disability (Anaby et al., 2017). Only 3% of current interventions for CP address environmental factors, and < 1% address personal factors (Novak et al., 2020), highlighting the need for greater emphasis on these domains in the clinical management of children with CP (Novak et al., 2013).

Caregiver support (e.g., physical support, verbal cues) is one contextual factor to consider in the promotion of motor skills and independence of children with disability (Dusing et al., 2019). Caregivers are moderators who may "drive or impede a change" in development through child-caregiver interactions (Dusing et al., 2019, p. 660). Research indicates that the ability of caregivers to sensitively respond (via, e.g., reciprocity, affect) is more important in developmental improvements than the intensity of therapy in children with a range of intellectual and motor disabilities (Atkins-Burnett & Allen-Meares, 2000; Karaaslan et al., 2013).

Given these findings, an important role of physical and occupational therapists may be to train caregivers to interact with their child in a way that bootstraps the child's skills and promotes independence. Caregivers must be adaptable in order to facilitate motor task performance, leading when needed, or following the child's lead when the opportunity arises. Depending on the task, there may be an optimal degree of caregiver leading/following, and deviation from that optimal level could be problematic. For instance, a caregiver may take over a functional task for the child, resulting in successful task outcomes but stifling child participation, or a caregiver may give the child too much independence, resulting in increased child involvement but unsuccessful task outcomes. Currently, however, therapists lack the necessary assessment tools to determine *when* to intervene and the necessary knowledge about factors that lead to ineffective interactions to know *how* to intervene (Dusing et al., 2019).

Overcoming this knowledge gap starts with the development and application of methods to objectively characterize the interaction dynamics of children with CP and their caregivers—that is, to characterize how their interaction unfolds over time. Researchers have examined interactions between caregivers and children with CP through a dynamical lens with emphasis on understanding the impact on speech/communication development (e.g., Pennington et al., 2004) or parental distress

(Barfoot et al., 2017). In physical and occupational therapy, the role of the caregiver is typically studied in terms of adherence to an intervention program (e.g., D'Arrigo et al., 2018), not the actual interaction taking place between the child and caregiver (Dusing et al., 2019). The present study provides, for the first time, a multi-modal description of dynamic interactions of typically developing (TD) children and children with CP with their respective caregivers during the performance of a collaborative motor task. Such a description is instrumental for the identification of (a) features of child-caregiver interactions related to ineffective caregiver support that should be detected by clinical assessments and (b) modifiable factors related to ineffective support that should be addressed by interventions.

Our aim is to offer new, clinically relevant, and data-driven hypotheses about these important features of interactions and modifiable factors to be examined by future studies. As such, the current work is—by nature—exploratory, laying essential groundwork in an underexplored domain stemming from basic research in joint action. We selected a motor task (Abney et al., 2015) that becomes more difficult over time, allowing for the analysis of unfolding child-caregiver interactions during particularly challenging (and hence potentially more informative) periods. In this task, the dyad is asked to construct the tallest tower possible out of raw spaghetti and marshmallows within a limited time window. The task also facilitates the emergence of a leader–follower dynamic predicated by the action possibilities assigned a priori to each member of the collaborating pair. For example, children and caregivers were only allowed to hold particular building materials: Children held the spaghetti pieces; caregivers held the marshmallows. Given this experimental constraint, it was expected from previous work that performance would improve if the marshmallow holder (i.e., the caregiver) led, based on the intrinsic task organization (Abney et al., 2015). Thus, the pattern and stability of the child-caregiver interaction dynamic might be a useful index of a caregiver's responsiveness to the child's action possibilities—an important feature of effective caregiver support.

Method

Participants

A convenience sample of 6 children with CP (8–11 years) and 6 age- and gender-matched TD peers (8–12 years) and their caregivers (38–51 years) participated. All caregivers were biological or adoptive mothers. The primary language for all participants was English. See Table 1 for complete demographics. Participants with CP were recruited from an academic pediatric medical center in the midwestern United States. Only participants with CP with mild motor impairments were included. Participants with CP whose impairments (e.g., blindness, deafness, executive function) would interfere with their ability to participate were not included. TD children were not included if they presented with a physical disability or recent (< 6 months) upper extremity musculoskeletal injury. Caregivers provided consent for their own participation as well as for the participation of their child, and each child provided assent.

Table 1 Participant characteristics

Characteristic	CP	TD
Child Age (years)	10.2 (1.4)	10.3 (1.4)
Caregiver Age (years)	42.8 (4.8)	42.5 (4.0)
Child Dominant Hand		
Left/Right	4/2	0/6
Caregiver Dominant Hand		
Left/Right	0/6	0/4
Child Race/Ethnicity		
African American	1	
Asian	1	
Caucasian	4	6
Caregiver Race/Ethnicity		
Caucasian	5	4
Hispanic	1	
CFCS Level I/II/III	5/0/1	NA
GMFCS Level I/II	4/2	NA
MACS Level I/II/III	4/1/1	NA
Hemiplegia/Diplegia	4/2	NA

CP cerebral palsy, *TD* typically developing, *CFCS* Communication Function Classification System, *GMFCS* Gross Motor Function Classification System, *MACS* Manual Ability Classification System, *NA* not appliable

The study was reviewed and approved by the University of Cincinnati Institutional Review Board.

Materials & Procedure

The procedure was adapted from Abney et al. (2015). Each member of the child-caregiver dyad sat across from each other in chairs at a small table oriented in the line of sight of a camera (Windows 10 Camera; Microsoft Corp., Redmond, WA). Seating arrangement was self-initiated. Once seated, participants were outfitted with a magnetic motion capture (Polhemus Patriot; Polhemus, Colchester, VT) marker placed on the dorsum of the dominant hand to record upper extremity position in the *x*, *y*, and *z* planes during the task, at a rate of 60 Hz.

The experimenter instructed participants to construct the tallest tower structure in 10-min using only the materials provided: one box (~ 10 oz.) of large marshmallows and one box (~ 1 lb.) of raw spaghetti. The position of the boxes on the table was randomized between dyads. To enforce interaction, only the child was permitted to touch the spaghetti, and only the caregiver was permitted to touch the marshmallows. Participants could not use partial or broken materials and had to remove any materials that broke during tower construction. The same experimenter monitored the compliance of all pairs with the task instructions and reminded participants if they violated them.

Participants had the opportunity to ask questions prior to data collection and were encouraged to talk freely during task performance. Dyads were provided with a 1-min warning before being asked to end the task.

Measures & Data Analysis

Data processing and analyses were completed using custom R scripts (v.3.5.1) in the RStudio (RStudio, Inc., Boston, MA) integrated development environment. ELAN (v.5.2) transcription software (Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen, The Netherlands) was used for coding video files.

Tower Measures

The presence of a free-standing tower at the end of the 10-min period denoted task success. Tower height was measured from the base of the structure to the highest point of the structure, if applicable. We also coded video files for the addition or loss of building materials on the tower. This allowed for a minute-by-minute analysis of progress and the identification of challenging periods (i.e., periods that included ≥ 50% of each dyad's total breaks and/or materials removed).

Movement Coordination & Leader–Follower Dynamics

We computed the overall Euclidean displacement (i.e., the difference in position from frame-to-frame) from the position data of the dominant upper extremity from each member of the dyad (Fig. 1a and b). Data were filtered using a low-pass, 4^{th}-order, Butterworth filter with a cut-off frequency of 6 Hz. The first 6 s of data were removed from each dyad's trial prior to analysis to account for the delay between the start of the Polhemus and the start of video recording and/or lag in participants beginning the task. We further subdivided data files into 1-min epochs to assess changes in the interaction over the construction period by subjecting each 1-min time-series to cross-recurrence quantification analysis (CRQA) (Marwan & Kurths, 2004).

The mathematical description of CRQA is documented extensively elsewhere (e.g., Coco & Dale, 2014; Marwan & Kurths, 2004; Marwan et al., 2007), so we limit ourselves here to a conceptual description. CRQA quantifies the shared locations or states (i.e., cross-recurrence) of two time-series. These shared locations are illustrated as dark points on cross-recurrence plots (CRPs; see Fig. 1c). Patterns of the points on CRPs (e.g., the number and length of diagonal lines in the plot) can then be quantified to provide insights into how the two time-series unfold together over time.

For the current study, we assessed instances of cross-recurrence between child and caregiver upper extremity movements. We quantified cross-recurrence using two metrics that capture coordination dynamics: *determinism* (DET) and *maximum*

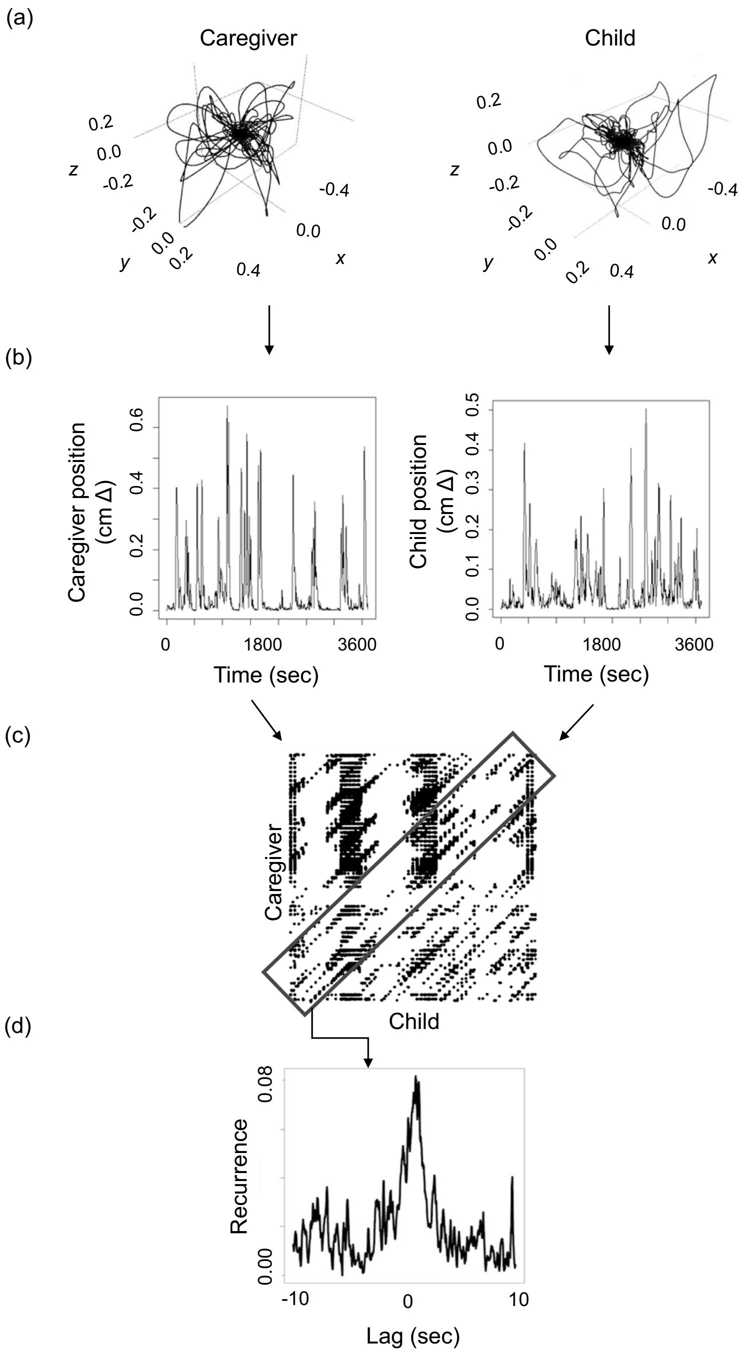

Fig. 1 Data processing. Raw *x, y, z* position of child and caregiver movement (**a**) transformed to two time-series (both child and caregiver) of the overall Euclidean displacement (**b**). These time-series were then subjected to CRQA analysis (**c**) and subsequent DWCR (**d**). Data are from a sample CP dyad. DWCR indicated near synchrony (i.e., close to zero lag) for this particular dyad during epoch 2

line length (MAXLINE). DET is the percentage of points that form diagonal lines in the CRP. Higher DET indicates that the coordination between members of a dyad is more deterministic or structured (as opposed to more stochastic). MAXLINE is the length of the longest diagonal line in the CRP (i.e., the longest period in which two signals occupy the same area); higher values indicate a longer period of continuous coordination (or increased stability of coordination) between members of a dyad. Importantly, as with all recurrence metrics, MAXLINE and DET are not absolute quantities; therefore, we consider the *relative* pattern of change in these metrics as most important for the goals of this study. For more on recurrence metrics and their interpretations, see Coco and Dale (2014), Marwan and Kurths (2004), and Marwan et al. (2007).

CRQA also allows for a unique analysis of leader–follower dynamics, using diagonal-wise cross-recurrence (DWCR; Coco & Dale, 2014). Essentially, DWCR considers a narrower band of the entire CRP—a window around the main diagonal of the plot (where $x=y$), also known as the *line of incidence* (or LOI; e.g., Dale & Spivey, 2006; Davis et al., 2017), depicted in Fig. 1c as a diagonal box. In the current study, we restricted this window to ± 10 s around the LOI for each 1-min epoch, allowing us to investigate the shorter-term leader–follower dynamics associated with effective caregiver support. Recurrence points that fall on the LOI represent moments where two time-series (here, the position time-series of caregiver and child hand movements) exhibit 0-lag synchronization. Recurrence points that fall on diagonal lines above or below the LOI indicate situations in which two time-series are coordinated with a lag (i.e., one is leading the other). MAXLAG is a metric of DWCR that indexes the lag at which cross-recurrence is highest within the set window around the LOI. Accordingly, a MAXLAG of 0 indicates that the most frequent child-caregiver interaction was perfect synchrony. A positive or negative MAXLAG would indicate that the maximum number of recurrent points in a single diagonal falls above or below the LOI (respectively); this would mean that similarities in child-caregiver movement occurred most frequently with a lag (i.e., one was leading/following the other). In this study, negative MAXLAG values indicated child-leading dynamics, whereas positive values indicated caregiver-leading dynamics (see Fig. 1d).

Language Structure

Following an initial transcription of dyad utterances, we coded language for three primary categories: imperatives, interrogatives, and other. Table 2 includes an explanation of these categories with coding criteria and examples. We included three additional categories: inaudible utterances, nonword sounds (e.g., laughing), and utterances directed to the experimenter. Two researchers who were not involved in data collection independently coded all videos for the aforementioned language categories. Each coder received a manual with instructions to assure consistency. Reliability between coders across the six categories was assessed using Cohen's kappa. Kappa exceeded 0.85 in each dyad; overall kappa for all dyads was 0.93, indicating a high level of agreement (Cohen, 1960).

Table 2 Transcription coding criteria and examples

Imperative—Phrases taking an imperative form of a command to partner	Interrogative—Questions directed at partner either through grammar or inflection	Other—Phrases that are neither in the imperative form or a question
"Work with me, Mother. Work with me."	*"Is that as high as you think we can go?"*	*"Well this is just a mess."*
"Hold the marshmallow. Just hold the marshmallow."	*"Okay, but do you think that's [going to] help it from tilting like this?"*	*"You understand why Mom isn't an architect or a builder of any kind."*
"Okay, hold that one in the middle so it doesn't break."	*"Can you hold it?"*	*"I think our tower is done. Because I am no good at building anything. Except relationships."*

As a measure of child-caregiver dynamics at the level of communication, we quantified the ratio of imperative statements to interrogative statements. To derive this ratio, we divided the imperative count by the sum of the imperative and interrogative count for each participant during each 1-min epoch. The resulting ratio indicated equal imperative and interrogative use (0.50), greater imperative than interrogative use (> 0.50), or greater interrogative than imperative use (< 0.50). We also assessed speech duration by dividing the duration of child speech by the duration of caregiver speech. The resulting ratios indicated greater caregiver speech (< 1.0), greater child speech (> 1.0), or equal speech (1.0).

Results

Task Success and Progress: Tower Measures

A dyad including one child with CP and their caregiver (hereafter referred to as CP dyads) and five of the six pairs of TD children and their caregivers (hereafter referred to as TD dyads) each constructed a free-standing tower by the end of the building phase. TD dyads and successful dyads deposited materials at a greater rate on their towers (i.e., increased slope) compared to CP dyads and unsuccessful dyads, respectively (Fig. 2).

Most structural failures (≥ 50% of each dyad's total breaks/materials removed) occurred during epochs 7–9 (T7-T9) for all but one dyad. This period included 70.6% (24/34) of total breaks or material removal for CP dyads and 40.7% (11/27) of total breaks or material removal for TD dyads. Thus, T7-T9 represented a particularly challenging period of tower construction, especially for CP dyads. One TD dyad experienced increased structural failure (≥ 50% of total breaks/materials removed) during epoch 1 (T1).

The measures of motor coordination (MAXLINE and DET) and leader–follower dynamics (MAXLAG) to be discussed next were computed to characterize (a) the overall pattern of child-caregiver interactions throughout the entire duration of the task and (b) the pattern of coordination during the most challenging period of the task. To index (a), we computed the average of the target measure over all of the 1-min epochs of the upper extremity position time-series. To index (b), we used the target measures obtained during the epochs that showed the greatest material loss.

Motor Coordination: MAXLINE and DET

For MAXLINE, the high inter-dyad variability in both (a) and (b) is noteworthy (Fig. 3a). Neither overall MAXLINE nor MAXLINE during the challenging period in isolation seemed to differentiate the behavior of successful dyads from the behavior of unsuccessful dyads. However, informative patterns did emerge when we examined how each dyad modulated coordination during their most challenging period (open markers) taking their own overall measures of coordination (filled markers) as a benchmark. TD dyads who were successful (triangular markers) demonstrated

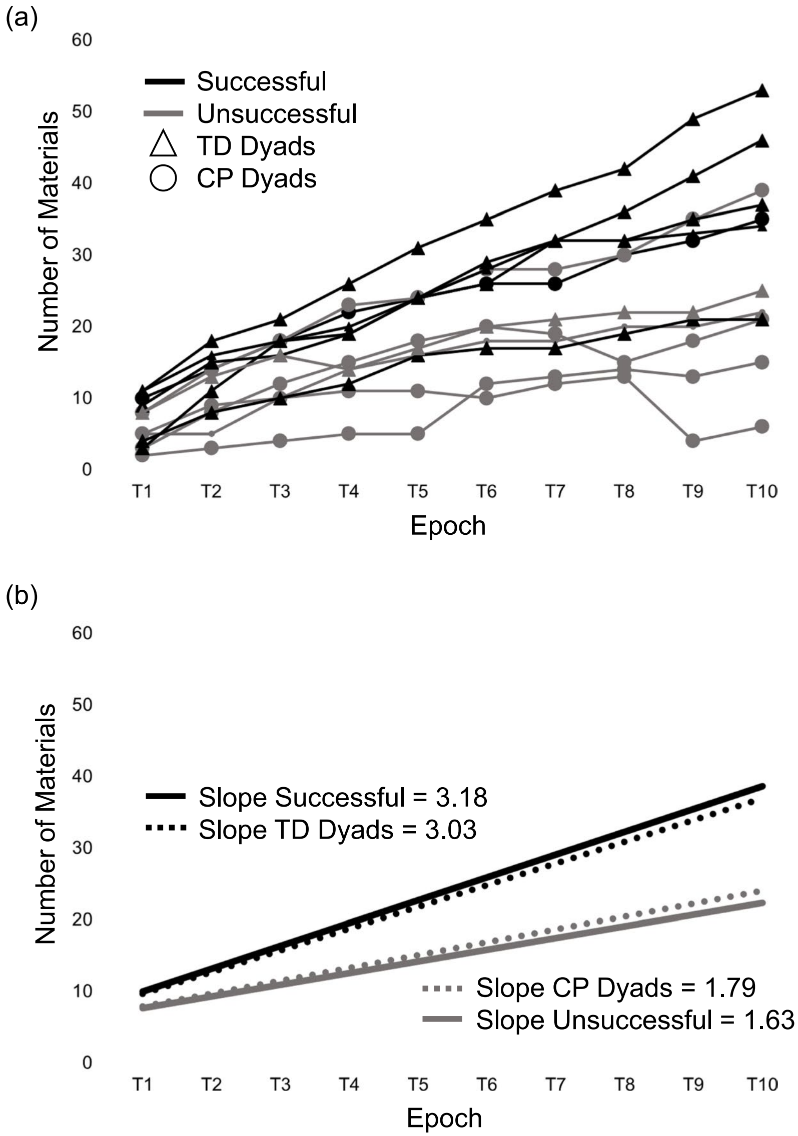

Fig. 2 Tower materials slopes. **a** Total materials (at the end of each 1-min epoch) plotted against time for each dyad. **b** Overall slopes by task success and group

an increase in MAXLINE (M_{diff} = 27.91, SE = 12.07) during the challenging period. Dyads who were unsuccessful (circle markers) demonstrated a decrease in this measure (M_{diff} = −28.21, SE = 6.35). All CP dyads, including the successful dyad, demonstrated a decrease in MAXLINE during their challenging period from their overall values (Fig. 3a). Thus, while an increase in the stability of coordination

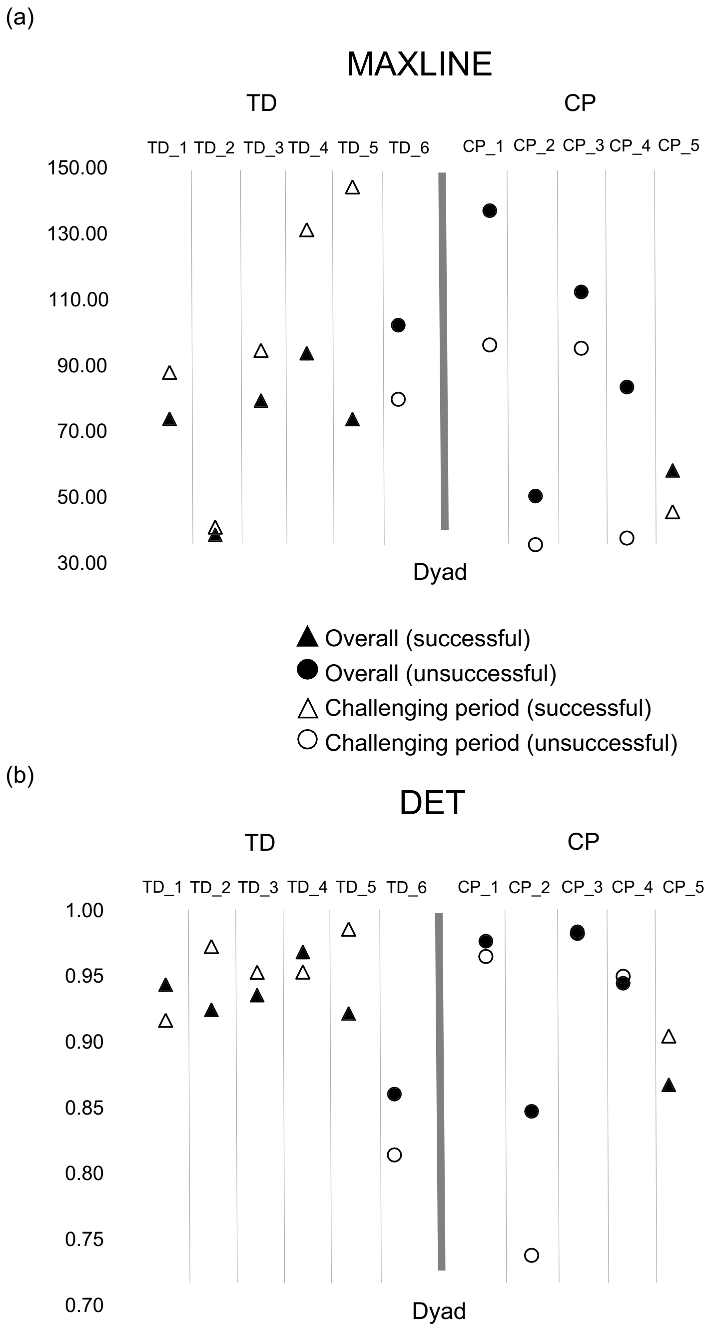

Fig. 3 Motor coordination. **a** Maximum line length (MAXLINE). Individual TD dyads demonstrated an increase in MAXLINE during the period with increased structural failure compared to their overall MAXLINE (averaged over entire 10-min duration). CP dyads demonstrated a decrease in MAXLINE during the challenging period compared to their overall MAXLINE. **b** Determinism (DET). Unsuccessful dyads showed a decrease in DET or little change from their overall DET during the challenging period. Data points for CP_3 are overlapping

during the challenging period seems to be related to task success, it does not seem to be a necessary condition for capturing effective support.

For successful TD dyads (triangle markers, Fig. 3b), DET was consistently high ($M = 0.938$, $SE = 0.008$). The only TD dyad who was not successful in the task showed nominally lower overall DET (0.860), which was further reduced during the challenging period (0.814). DET was more variable (i.e., higher SE) for CP dyads ($M = 0.924$, $SE = 0.03$). Importantly, however, for the CP dyads who were unsuccessful, DET either did not change or decreased during the challenging period. For the successful CP dyad, DET increased through the challenging period. Thus, unsuccessful interactions seem to be associated with a deterioration of coordination, characterized by a loss in both its deterministic structure and stability. It is possible, therefore, that successful child-caregiver interaction is predicated on a sensitivity to the task context, such that at least one aspect of coordination is enhanced (indexed by either an increase in MAXLINE or DET).

Leader-Follower Dynamics: MAXLAG

The inter-individual variability in overall MAXLAG sign and magnitude is also noteworthy (see Fig. 4). Informative patterns again emerged when we examined how each dyad modulated leader–follower dynamics during their most challenging period (open markers) compared to their own overall leader–follower dynamics (filled markers). Successful dyads (both CP and TD) either maintained the overall dynamic of caregiver leading or assumed caregiver leading during the challenging period. The unsuccessful dyads (both CP and TD) either maintained their overall dynamic of child leading or exhibited child leading during the challenging period, with only one exception (CP_2). During the challenging period, the child tended to lead in CP dyads ($M = -1.54$ s, $SE = 1.83$), while the caregiver tended to lead in TD dyads ($M = +1.14$ s, $SE = 1.45$). Similarly, the child tended to lead in unsuccessful dyads ($M = -2.63$ s, $SE = 1.87$), and the caregiver tended to lead in successful dyads ($M = +1.97$ s, $SE = 0.66$). Of course, we recognize the inherent difficulty in disentangling these two dimensions from the current dataset, given the uneven distribution of successful versus unsuccessful dyads across CP and TD dyads.

Language Structure

Caregivers spoke more than children (i.e., child/caregiver ratio < 1.0), regardless of group or task success (CP: $M = 0.67$, $SE = 0.22$; TD: $M = 0.84$, $SE = 0.38$; successful: $M = 0.81$, $SE = 0.38$; unsuccessful: $M = 0.70$, $SE = 0.22$). On average, caregivers in CP dyads used more imperatives (i.e., directives/commands) than interrogatives (i.e., questions; ratio > 0.50; $M = 0.65$, $SE = 0.05$) whereas caregivers in TD dyads used more interrogatives ($M = 0.45$, $SE = 0.05$; see Fig. 5a). Children in CP dyads used more interrogatives ($M = 0.46$, $SE = 0.04$) whereas children in TD dyads used more imperatives ($M = 0.70$, $SE = 0.03$; see Fig. 5b). These results suggest that children were more directing in their language compared to their caregivers in TD dyads, while caregivers were more directing in CP dyads.

This trend held across successful (caregiver: $M = 0.48$, $SE = 0.04$; child: $M = 0.59$, $SE = 0.03$) and unsuccessful (caregiver: $M = 0.62$, $SE = 0.05$; child: $M = 0.54$, $SE = 0.05$) dyads. During the challenging period, children in CP dyads decreased imperatives while their caregivers demonstrated little change in imperative use. This did not occur in TD dyads. See Fig. 5c for individual dyad data.

Discussion

Contextual factors are fundamental to the daily functioning of children with CP but are widely understudied in pediatric physical and occupational therapy (Novak et al., 2013, 2020). The current study conducted exploratory analyses to provide initial insights about a particular contextual factor: caregiver support. We specifically aimed to derive novel, clinically relevant, and data-driven hypotheses for future studies about features that might be used to index effective child-caregiver interactions, which we operationalized as interactions that resulted in task success. There has been a push to incorporate assessments of child-caregiver interactions into clinical practice and research, but barriers to implementation exist (Dusing et al., 2019). One of the primary barriers noted is the therapist's ability to identify the components of an effective interaction.

Recent work (Toro & Martiny, 2020) examining child-caregiver interactions in children with CP and their caregivers during the performance of *familiar tasks* (e.g., playing patty-cakes, passing cups of water) suggests that caregivers may be implicitly aware of how to manage daily tasks in a manner most appropriate for their child (in contrast to strangers). The current work provides preliminary evidence of somewhat distinct dynamics that emerge during a novel task, particularly when the task becomes challenging: Caregivers of children with CP (as well as caregivers of TD children) may modify their own behaviors, and the presence or absence of behavioral modification may be related to ultimate task success. Some modifications found in TD dyads were not found in CP dyads. For instance, during the challenging period, caregivers in CP dyads demonstrated little change in imperative use. Given the findings of Toro and Martiny (2020), caregivers in CP dyads may implicitly adopt this strategy based on experience with familiar tasks; however, a different strategy may be required for novel motor tasks. This paper offers, for the first time, candidate objective metrics for effective support that can help in understanding such findings and increasing assessment of interactions in the clinic. Table 3 summarizes the data that guided the formulation of future hypotheses, which we present in turn.

Future Hypothesis 1: Successful Collaborative Motor Task Performance—and, by Extension, Effective Child-Caregiver Motor Interaction—Shows Enhanced Child-Caregiver Coordination and a Task-Sensitive Leader–Follower Dynamic During Challenging Periods of the Task

Results showed that the modulation of coordination strength and leader–follower dynamics when task performance became challenging was particularly informative

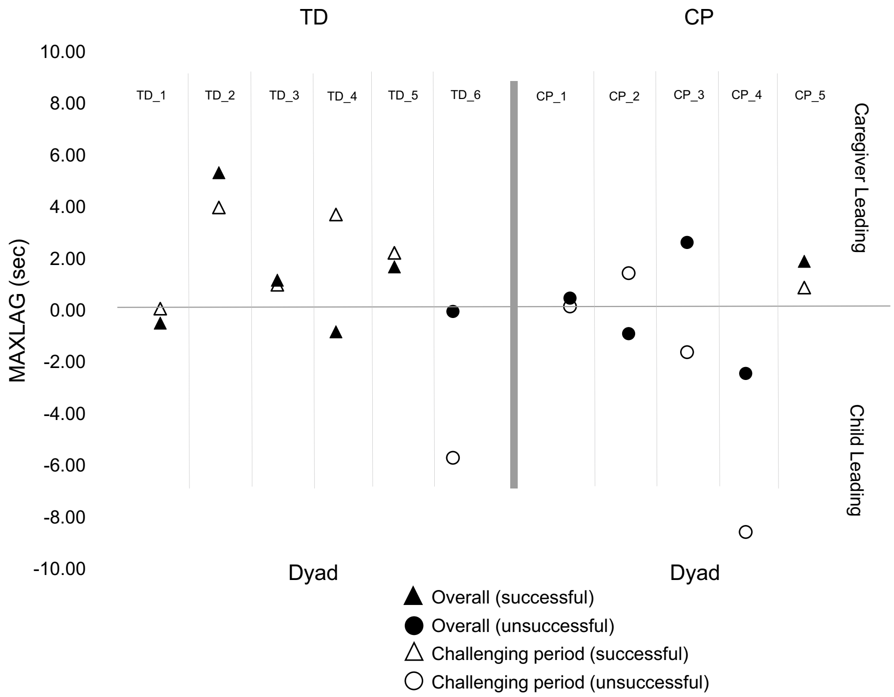

Fig. 4 MAXLAG by group. Overall results (averaged over entire 10-min duration) and period with increased structural failure presented for each dyad. TD dyads and successful dyads either maintained caregiver leading or assumed caregiver leading during the challenging period of construction. Unsuccessful dyads either maintained child leading or assumed child leading during the challenging period (except CP_2)

of the effectiveness of child-caregiver interactions. In particular, ineffective interactions (i.e., interactions of dyads who did not succeed in building a free-standing tower) were characterized by a weakening of child-caregiver coordination in the period of increased structural failure (see Table 3). Therefore, successful child-caregiver interaction may be predicated on sensitivity to changes in task demand, such that at least one aspect of motor coordination is enhanced: either its deterministic structure (indexed by an increase in DET) or its dynamic stability (indexed by an increase in MAXLINE). While some dyads demonstrated patterns of high coordination when averaged over the entire 10-min trial, if those dyads did not increase motor coordination further when the task became challenging, they were unsuccessful at the task.

As noted, the tower building task we selected imposes a particular leader–follower dynamic due to the action capabilities prescribed to each member of the dyad: Marshmallow holders are better situated to lead through the positioning of the marshmallow, and spaghetti holders follow. When two TD adults perform this task, they seem to attune to this task dynamic—that is, marshmallow holders tend to lead in successful dyads (Abney et al., 2015). Our results showed greater variability in leader–follower dynamics than what Abney et al. (2015) observed,

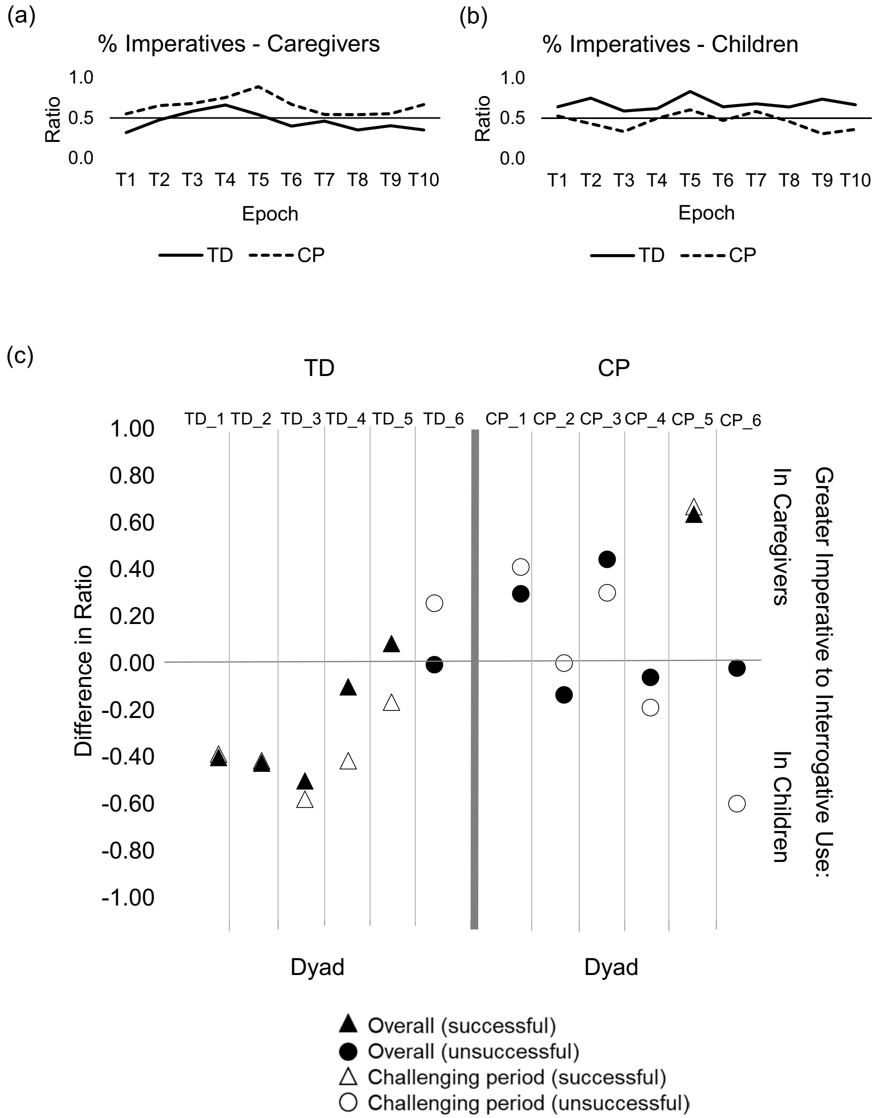

Fig. 5 Language structure. Mean percent imperative use in caregivers (**a**) and children (**b**) at each 1-min epoch (in relation to total imperative and interrogative use). Values indicate equal use of imperatives and interrogatives (0.50), greater imperative use (> 0.50), or greater interrogative use (< 0.50). **c** Individual dyad differences between percent imperative use in caregivers and children, indicating greater relative imperative use by the caregiver (> 0.0), by the child (< 0.0), or equal use (0.0). Data points for TD_1 and TD_2 overlapping

although we cannot be sure from the current work what may be driving these differences given the substantially different populations. Notably, however, in child-caregiver dyads that succeeded, the caregivers (marshmallow holders, in our case) either consistently led the interaction or took the lead when the task became

Table 3 Results summary

Dyad	↑ MAXLINE or DET during challenging period	Caregiver leading during challenging period	Imperative language by child during challenging period	Slope of materials > 2.0	Successful (Y/N)
TD_1	X	X	X	X	Y
TD_2	X	X	X	X	Y
TD_3	X	X	X	–	Y
TD_4	X	X	X	X	Y
TD_5	X	X	X	X	Y
TD_6	–	–	–	–	N
CP_1	–	–	–	–	N
CP_2	–	X	X	–	N
CP_3	–	–	–	–	N
CP_4	X	–	X	–	N
CP_5	X	X	–	X	Y

The first three columns offer candidate indices of effective support, the last two columns provide metrics of task success. Due to a technical error during collection, we were unable to obtain movement coordination data for CP_6, and thus, have excluded this dyad from the aggregate summary identifying candidate indices of effective support

CP cerebral palsy, *TD* typically developing, *MAXLINE* maximum line length, *DET* determinism

challenging. Again, while some dyads demonstrated more overall caregiver leading, if caregivers did not maintain the lead during the challenging period, the task tended to fail. Consistent with previous work in TD adults, effective joint action in novel collaborative tasks is grounded in the ability not only to generate complementary action but to do so at the *appropriate time* (Sebanz et al., 2006).

Implications of Hypothesis 1

Support for this hypothesis in future research could lead to the development of clinical assessments and interventions: Critical aspects of motor tasks may be identified, and caregivers may be trained to identify and respond appropriately during these periods. Relatedly, less challenging periods of the task may be an opportunity for child-led, independent movement. Future work can empirically assess if explicit caregiver awareness of a challenging period (across a variety of tasks) can facilitate other aspects of the interaction (e.g., motor coordination).

The methods available for assessing child-caregiver interactions in physical and occupational therapy research and practice are typically restricted to behavioral coding or scoring videos with itemized checklists (Dusing et al., 2019). In the current study, we provided an analytical method that *objectively quantifies* child-caregiver interaction dynamics in terms of *movement*. This is particularly valuable, considering that pediatric physical and occupational therapists work with children with movement disabilities. This is a critical contribution supporting research going forward in this domain, and we encourage researchers working in this nascent area to consider use of the analytical strategies employed in the current work. It may also be beneficial to evaluate how these objective movement indices (e.g., DET, MAXLINE) map onto more commonly used clinical tools for assessing interactions.

Future Hypothesis 2: Simple Language Structure does not Predict Collaborative Motor Task Outcome or the Effectiveness of Motor Coordination Dynamics

Increased imperative use in children along with increased interrogative use in caregivers during the challenging period was identified as a candidate index for effective caregiver support (Table 3). However, the results of the current study do not lend support for a particular language structure being an important property of effective interaction. For instance, two CP dyads demonstrated increased imperative use in children but were unsuccessful at the task. Further, the successful CP dyad did not demonstrate increased child imperative use. Meanwhile, the successful TD dyads demonstrated increased imperative use by children. While there were some interesting differences in the average language structure across groups, our small sample requires that we consider individual patterns and not over-interpret these averages. As mentioned previously, the task dynamic of the current study had an intrinsic role-sensitive organization, with improved performance when the marshmallow holder (i.e., the caregiver) led the task. Our results, then, do not support a simplistic approach to connecting specific language constructions to task success; much like our motor analyses, more nuance—and, perhaps, context-sensitivity—may be required. However, implementing a simplistic approach in the context of the current study provided useful insights, as this may be the most feasible level of analysis for a clinician to target via intervention.

Implications of Hypothesis 2

Future work may investigate if a task without an intrinsic a priori role-sensitive organization (i.e., a task in which roles emerge spontaneously) allows language structure to become a marker of effective support. Although we were not able to demonstrate the influence of language structure in an effective interaction within this sample, future work may investigate whether constraining dyads to a particular language structure (e.g., interrogative structure) facilitates enhanced motor coordination and, ultimately, task success. A more elaborate language coding scheme should also be considered to address the potential for supportive versus intrusive directive language, which seem to have different roles in conversation (Flynn & Masur, 2007).

Simultaneously, future work should take a *dynamic* approach to understanding child-caregiver language during these collaborative interactions. We recommend that future basic research may take a context-sensitive approach to language (e.g., Fusaroli et al., 2012), acknowledging that some patterns of language dynamics may be helpful or hurtful based on context. More dynamic language analysis tools (e.g., Duran et al., 2019), including applications of CRQA to categorical language data (e.g., Cox & van Dijk, 2013; Dale & Spivey, 2006; Lira-Palma et al., 2018), may also facilitate new insights by investigating different dimensions and timescales of language.

Future Hypothesis 3: Candidate Indices of Effective Interactions are Less Frequently Observed in CP Dyads than TD Dyads

The candidate indices for effective interaction identified here were found less often in CP dyads than TD dyads. Specifically, during a particularly challenging period of construction, child-leading was found in CP dyads, while TD dyads demonstrated caregiver-leading. Further, TD dyads demonstrated higher motor coordination during challenging periods from their overall averages, while CP dyads demonstrated lower coordination, perhaps contributing to the structural failure observed in this period and to the overall unsuccessful task performance.

Collectively, the discrepancies between groups may suggest that TD dyads are more responsive in adapting their coordination dynamics to the properties of the changing task than CP dyads. The asymmetries in task demands (from each member's skill and physical ability) may have been more pronounced in CP dyads than in TD dyads. It is important to note, however, that the children with CP in this study had only very mild functional impairments. The reduced caregiver responsiveness observed may therefore be magnified in children with a higher level of disability where there are greater asymmetries between the abilities of the child and the caregiver.

However, because we take a *dyadic* and *dynamic* approach to understanding these interactions, we cannot say with the current data what may be driving this effect: Caregivers' reticence to initiate leadership, children's reticence to relinquish leadership, some combination of these two, or neither of these may have been the cause of this emergent dyad-level behavior. We also did not inquire about dyads' intentions or strategies; self-reports—coupled with further observable data—may be critical in understanding contributors to these dynamics. At this point, we can only say that CP dyads did not demonstrate the same dynamics that were associated with success in TD dyads.

Implications of Hypothesis 3

These candidate indices for effective child-caregiver interaction may be particularly pertinent for interventions in CP. Although these indices were present less often in CP dyads, the only successful CP dyad enhanced coordination and maintained the task dynamic during the challenging period. This provides preliminary support for our hypothesis and suggests that caregiver responsiveness may be a candidate for modification through intervention. If Hypothesis 3 is supported by future experimental work, future interventions may be developed to increase *task-relevant* caregiver responsiveness as a kind of scaffold for success for children with CP. Future work should explore whether these patterns hold across levels of disability (given that the children with CP in our study had only very mild functional impairments) and the possible downstream consequences of reduced caregiver responsiveness on a child's functioning and disability.

However, given the uneven distribution of task success in the data, it is possible that different dynamics are predictive of success for CP dyads than for TD dyads.

In other words, successful dynamics for CP dyads may not necessarily look like successful dynamics for TD dyads, and there may be other strategies of child-caregiver interaction that emerge among successful CP dyads. In generating this future hypothesis, we are creating a less biased starting point for future work, acknowledging that the task may not have facilitated the strategies that are used by children with CP to effectively interact with their caregivers for successful task performance. Importantly, our sample demonstrates both that CP dyads can succeed and that TD dyads can fail, which will be a requirement for any task used in future work (as discussed further in the next section).

Limitations

The sample size of this exploratory study limits the generalizability of results. Our sample also only included children with mild impairments which further limits generalizability. Future research should increase sample size to complete formal testing of the hypotheses proposed in this work with differing levels of disability. It is also important to test our hypotheses across a variety of functional tasks as well as complete subgroup analyses to account for possible moderators (e.g., age, functional ability, gender). We did not counterbalance which participants held the marshmallows and spaghetti. This was a choice made in part because of the small sample size, rendering it difficult to make multiple between-group comparisons. While the study included 12 unique child-caregiver pairings, two caregivers of TD children previously completed the task as they each had two children participate in the study to meet the age- and gender-match criteria. It is interesting to note that these caregivers used different interaction strategies when working with each of their children (e.g., increased use of imperatives versus interrogatives), which provides a potentially fruitful direction for future research in examining how interaction strategies change between caregivers and siblings, particularly if one sibling has CP and the other is TD. It also provides additional impetus to examine the moderators that can influence child-caregiver interactions. Given the exploratory nature of this study, this limitation did not interfere with the achievement of our objectives, however, we do acknowledge this as a limitation, as shared experiences outside of the study may have influenced the interactions observed.

A critical limitation of the current study lies in the distribution of success and failure among CP and TD dyads: Only one CP dyad succeeded in the task, while only one TD dyad failed. As a result, it is difficult to disentangle these two variables. In order to test the impact of child-caregiver dynamics on success, future work should investigate whether larger samples will lead to greater numbers of successful CP dyads and unsuccessful TD dyads. If not, future work may consider altering the task (e.g., extending the time limit, imposing a height limit rather than a time limit) to facilitate more equal distributions of outcomes among CP and TD dyads, allowing researchers to explore how child-caregiver dynamics alone or in conjunction with disability status predict success.

Conclusions

Caregiver support is an important consideration for the development of successful motor task performance in children with CP. The results of our exploratory study point to the following hypotheses and future directions:

- Successful collaborative motor task performance—and, by extension, effective child-caregiver motor interaction—shows enhanced child-caregiver coordination and a task-sensitive leader–follower dynamic during challenging periods of the task.
- Simple language structure does not predict collaborative motor task outcome or the effectiveness of motor coordination dynamics.
- Candidate indices of effective interactions are less frequently observed in CP dyads than TD dyads.

These should be tested in future work and guide the development of therapeutic assessments and interventions targeting contextual factors in CP. Specifically, it is important to incorporate assessments of child-caregiver interactions into routine physical and occupational therapy practice and research (Dusing et al., 2019). Future work may also consider child-caregiver interactions in children with different functional abilities. Subsequent interventions may accordingly train caregivers to react implicitly to their child's action capabilities within a given task dynamic to facilitate task success and promote independence, the most highly prioritized outcome of physical and occupational therapy for individuals with disabilities (Angeli et al., 2019).

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Data Availability Conversation coding manual, conversation code, and movement coordination code available on the Open Science Framework (OSF): https://osf.io/stc83/

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

Ethics Approval 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 All participants > 18 years provided informed consent. Participants < 18 years provided informed assent, and their parents provided informed consent.

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