Is the effect of gross motor development on vocabulary size mediated by language-promoting interactions?

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Abstract: Previous research suggests there is a positive correlation between infants' motor and language development. Several reasons for this effect have been suggested, but little empirical research directly addressed them. Here we tested the hypothesis that motor development is related to an increase in language-promoting interactions with parents (such as naming objects that the infant is interested in), and that these activities are related to language development. 93 Israeli parents filled in questionnaires about their 8- to-18-month-old infants' language and motor development, as well as about their engagement in language-promoting interactions. Contrary to previous research, we found no evidence that motor development was related to language development, and only partial evidence that motor development was related to language-promoting interactions, and language-promoting interactions to vocabulary size. Possible reasons are discussed.

Keywords: motor development; language development; social interactions

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Introduction

During their first years of life, infants acquire motor skills that significantly alter the way their body moves, affects their environment, and is affected by it. New motor skills change the way infants interact with objects and people around them. Honing these motor skills includes different physical aspects such as manual dexterity and changes in posture and mobility, and allows infants opportunities to act on the world around them actively and proactively (Iverson, 2010, 2021).

Do infants who develop motor skills faster than others also develop faster linguistically? Some empirical evidence suggests that they do. Two recent systematic reviews found an overall positive correlation between motor and language skills (Gonzalez et al., 2019; Leonard & Hill, 2014). These findings have three general explanations, which are not mutually exclusive. We survey each before focusing on the third of these explanations - that new motor abilities change infants' relationship with their environment in a cascading manner (Iverson, 2010, 2021) - the explanation we explore in depth in the current study.

The shared-resources explanation

The first explanation is that motor and language skills share the same set of resources. When infants are engaged with acquiring a novel motor skill, such as learning to stand upright, they produce less vocalizations, being wholly absorbed in acquiring this new skill (Berger et al., 2017). Boudreau and Bushnell (2000) found an interference effect between motor and cognitive activities (and between cognitive and motor activities) in 12 months old infants, not only during transitional periods of mastering a new skill. They called this the attention-driven cognition/action trade-off. Overall, it seems that interference between motor and cognitive performance occurs when the demand for the second task is greater than the system's resource capacity (Abou Khalil et al., 2020). It stands to reason that infants with larger system resource capacity (e.g., larger attentional or cognitive capacities) would be better in both language learning and motor performance - which could explain why most previous studies do find a relation between motor and language skills. However, while there is a relationship between the onset of walking and vocabulary comprehension, this relationship becomes weaker after two weeks of walking experience (Walle, 2016; Walle & Campos, 2014). This seems at odds with a joint attentional resources view, as children with larger cognitive/attentional capacities should excel in both sets of skills and there would be no reason for this relationship to weaken.

The direct-physical-link explanation

The second general explanation is that motor development affects articulation through a direct, physical, route. The physical route is manifested in several motor millstones. Infants' ability to hold objects and bring them to their mouth is an effective way to explore vocal production. It was found that when 11- to-13-month-olds play, they produce sounds whose quality changes in relation to the size of objects they explore. When infants play with larger objects, they open their fingers wider, and also open their mouth wider, changing their vocal productions (Bernardis et al., 2008). Posture is another factor which affects the physical aspect of speech production. A vertical position of the head during upright sitting, for example, changes the way the vertebra and vocal cords are aligned, and the tongue is pushed towards the front of the mouth, making it easier to produce syllables (Yingling, 1981).

Another line of evidence that physical factors affect language development directly is evidence that children with articulation delay are prone to also show motor delays (Gaines & Missiuna, 2007), and infants with atypical motor development, such as cerebral palsy and preterm infants, tend to also show language delays (Ross et al., 2018). There is also a great amount of evidence for both language and motor delays in autistic children (Iverson et al., 2019; West et al., 2019), however, Autistic Spectrum Condition (ASC) is a pervasive condition affecting many areas, and could also be related to the cascading relation with the infant's environment (Iverson et al., 2022), so it will be discussed in detail below.

In surveying the physical route, we assume that its effect on language production will be stronger than its effect on language comprehension, since articulation will be most directly affected. However, strong ties and correlations exist between language production and comprehension. Even simple articulation processes may affect language comprehension. For example, research has shown that blocking the ability to temporarily produce certain phonemes during learning in infancy is related to the ability to discriminate between these phonemes (Bruderer et al., 2015; Choi et al., 2019). Nonetheless, since the effect of motor development on language production is more direct than its effect on comprehension, we suggest that larger gains in production than in comprehension following motor milestones would support the physical route, while larger or equal gains in comprehension will support the interactional route (detailed below) as well. This is because production involves a physical activity (articulation) which is either affected by physical abilities or even defined in itself as a fine motor skill.

Walking infants do show larger vocabularies in both production and comprehension than crawling infants of the same age (He et al., 2015; Walle & Campos, 2014; but see Moore et al., 2019 who do not find a relationship between the onset of walking and vocabulary size). Even when infants who did not yet walk independently were placed in walkers, they still produced less sounds and gestures, including pointing and capturing the mother's attention, than infants who could walk independently (Clearfield, 2011). This could mean that it was more than posture which affected speech and communication. Rather, infants' experience with the world as independent walkers might have affected their language and communication skills.

The cascading-effects explanation: changes in the relationship with parents and with the environment

The third general explanation is that by changing infants' relationship with the world around them, and especially with their caregivers, motor development causes a cascading effect of increasing language promoting activities and interactions (Iverson, 2010, 2021). We refer to this route as the interactional route, a route that is at the heart of the current study. We first describe motor skills' effect on infants' interaction with objects before describing social interactions.

Exploring objects by themselves allows infants, for example, to connect an object with its use and meaning (for example, when they put beads in a canister). Toddlers' manipulation of objects affords them a better view of the objects they are exploring than when parents manipulate the same object. Infants' view is more diverse and captures higher-quality object views than parents' view, and when neural networks were trained on child-generated data, they achieved better performance than when trained on adult-generated data (Bambach et al., 2018). In another study, Slone et al., (2019) found that infants who generated such object views through object manipulation at 15 months of age experienced greater vocabulary growth over the next six months. Moreover, infants attribute meaning to objects when they engage in recognition gestures (such as holding a phone to their ear). It has been suggested that naming an object using a word or a gesture begins with the motor act of using an object, such as a phone in the example above (Bates et. al.,1979). Such gestures are easier to perform when one can sit upright or stand, or move in space by crawling or walking to reach toys of interest.

On the social side, motor development also affords infants more opportunities to engage in language-promoting interactions with their caretakers (Iverson, 2010, 2021; West et al., 2019). For example, sitting without support allows a wider and more flexible field of vision (Iverson, 2010), which might increase the chances of creating eye contact and shared attention with parents. In addition, walking infants can pick up an object and bring it to their caretaker, creating joint interest and attention around an object that is especially attractive to the infant at that moment. Indeed, caregiver utterances contain more labels during infant object manipulation, and these labels frequently corresponded to the infants' held object and their gaze (West & Iverson, 2017).

Walle (2016) found that infant initiation of joint engagement such as bringing objects to the parent, as well as following of the parent's joint engagement cues such as their gaze, increased as a function of infant walking experience. Parents might also talk more to walking than crawling infants (Karasik et al., 2011; Schneider & Iverson, 2022), and tend to use verbs that correspond with the action the infant is engaged in (e.g., describing the action; West et al., 2022). West et al. (2023) found that while they were walking, 13- and 18-month-old infants received triple the rate of locomotor verbs compared to when they were stationary.

While the overall amount of speech directed to children (and possibly also overheard by them, see Akhtar, 2005, but cf Shneidman & Goldin-Meadow, 2012) is seen as extremely important for language development (Hoff & Naigles, 2002; Weisleder & Fernald, 2013), quality child-directed speech is seen as even more useful to their language development. Parents' congruent and thoughtful engagement with infants is thus a major contributor to their cognitive and linguistic development. Previous prospective research found that children whose mothers were more responsive during the first few years of life achieved language-development milestones earlier than those with less responsive mothers (Tamis-LeMonda et al., 2001; Paavola et al., 2006). Incidentally, Tamis-LeMonda et al. (2001) found stronger relations between responsiveness at 13 months and language milestones, then between responsiveness at 9 months and the same milestones - coinciding with the age at which most children begin to walk. Thus, in typically developing children, if motor development promoted such quality, responsive, and adapted child-directed speech - then it stands to reason that motor development supports language development indirectly through increasing adapted and useful linguistic interactions.

Such a cascading effect for motor development on language development has also been shown in children with ASC (West et al., 2019). ASC manifests itself in (among other things) qualitative impairments in communication including a delay in or total lack of development of spoken language. It also includes social atypicalities such as a lack of spontaneous seeking to share enjoyment, interests, or achievements with other people, or a lack of social or emotional reciprocity (Hodges et al., 2020) - the same processes thought to link motor and language development. Motor challenges in ASC are also very common, with up to 87% of the autistic population affected (Zampella et al., 2021). Given that all three of these fields (the social, the motor, and the language fields) are atypical in the autistic population, it is important to also examine whether a cascading effect can be directly viewed, rather than only through correlations between these three fields. Calabretta et al., (2022) tested links between infants' walking and parental responsiveness in typically developing children and siblings to autistic children - that were later diagnosed with, or not diagnosed with, ASC themselves. They found that out of all the infants' in the sample, infants' moving bids (infants' sharing with their caregivers of objects they carry from a distance, by approaching them and using gestures to show or offer their discoveries) were related to highly elevated parental responding with language. However, parents of siblings later diagnosed as autistic were more likely to respond when their infants simply approached them (with or without an object in hand). This particular finding demonstrates that cascading effects between motor abilities, proactive eliciting of language-promoting interactions by the infant, parental responsiveness and language outcomes in autistic infants are nuanced and merit further investigation. As motor-language cascades in ASC are not the focus of the current study, we refer interested readers to Iverson (2018) for a review of additional studies on the subject.

The current study

While we find the explanation of these cascading effects linking motor to language skills compelling, there are very few studies examining the mediating effect of language-promoting interactions in the relation between motor and language development in typically developing children (though see Walle, 2016; as well as West et al., 2019 who test an ASC and a typically-developing comparison group). Generally speaking, there is strong evidence that motor development promotes language-promoting interactions (e.g., Schneider & Iverson, 2022; Walle, 2016), and that language-promoting interactions are related to language development (e.g., Hirotani, et al., 2009), but less evidence that these interactions with infants mediate the relationship between motor and language development. In the current study we wanted to test this hypothesis using parental reports of motor development, language-promoting interactions, and language development in 8- to 18-month-olds. We chose this age range because it is a time of rapid development in both motor and language areas. In addition, the widely used vocabulary parental-report questionnaire, the Macarthur-Bates Communicative Development Inventory (Fenson et al., 1994), which was also used in the current study, only starts at 8 months of age. In terms of motor development, according to the Alberta Infant Motor Scale-AIMS (Darrah et al., 1998) norms, 90% of infants will have achieved unsupported sitting by 8 months, independent standing by 13 months, and independent walking by 14 months. Thus, we expected to find large variability in our sample in both domains.

There was some challenge with operationalizing the concept of language-promoting interactions. Interactions can either be initiated or led by the infant, or they can be initiated, led or controlled by the parent, as can be seen from the different examples above. Thus, parents could be compelled by the infant's motor abilities to behave in a certain, language-promoting way towards them, but motor development might also drive the infant's own behavior regardless of the parent. We generally hypothesized that motor development will be positively related to language development, as was previously found. We expected motor development to also be related to language-promoting interactions (which include both child-initiated and parent-initiated interactions). We expected, like previously found in the literature, these same language-promoting interactions to be related to language development. Last, we expected language-promoting interactions to mediate the effect of motor development on language development, as was notably suggested by Iverson (2010, 2021), as well as others (e.g., Walle, 2016).

Method

Participants

143 parents filled in at least some of the online questionnaires. Of these,102 filled in all questionnaires. Of these we excluded 9 infants: 5 were bilingual (over 25% exposure to a second language reported in the CDI demographic questions, based on the criterion in Frank et al. (2020), 3 were born preterm (more than 4 weeks early according to the CDI questionnaire demographic section - one of these infant was not reported as being premature in the CDI questionnaire, but was reported in our demographic questionnaire as being born on the 30th week of gestation and was therefore excluded), and 1 was below 8 months of age. Another exclusion criterion was parental reports of developmental concerns (these were screened for content, such that reports of non-serious issues - early treated torticollis, for example - could still be included). No parent of the included sample reported serious concerns. The mean age of these infants was 12.42 months (SD 3.24 months, 42% girls). Since we relied on norms for the the Hebrew Web Communicative Development Inventory, and norms were not available for 8-month olds, we removed these children from the analyses of their production, but not comprehension (see below in the Measures section for justification). The comprehension analyses thus included 93 infants, while the production analyses only included 81 infants, who were, on average, older (13.025, SD = 2.868, 38% girls). Out of these 93 infants, at the time of the study, parents reported that 84 were already crawling, 79 were standing unsupported, 75 were sitting unsupported, and 36 were already walking (see Table 1).

Design and Procedure

Parents were recruited online through social media. They filled in five online questionnaires: the gross-motor development subsection of the Ages and Stages Questionnaire (ASQ, to measure motor development), the Hebrew adaptation of the Communicated Development Inventory (CDI, to measure language development), a language-promoting interactions questionnaire developed in our lab, the StimQ home cognitive environment questionnaire (Availability of Learning Materials and Reading subscales), and a demographic details questionnaire. Parents signed online consent forms and the study was approved by the University of Haifa's IRB. The study was not preregistered but the data and analyses scripts, as well as the measure we developed are available on the OSF https://osf.io/hrmp6/?view_only=1248633dd1e943babdf316e4ed205191.

Measures

Ages and Stages (ASQ, Squires et al., 1997). This tool includes 21 separate questionnaires for 2- to-66-month-olds. Each questionnaire contains 30 items querying about five different areas of development: communication, gross motor, fine motor, problem solving, everyday activities and personal-social development. For each item the parent marks whether the infant performs this activity (10 points for "yes", 5 for "inconsistently" and 0 for "not yet"). We used only the gross-motor-skills subset of the instrument, and the forms for 8- to-18-month-olds. Overall, the ASQ has a re-test reliability of .94, and a high correlation (r = .88) with the Bayley Scales of Infant Development (Squires et al,1997). We translated the ASQ relevant forms to Hebrew, and back to English to ascertain the quality of translation before administering them.

The Hebrew Web Communicative Development Inventory - MB-CDI (Maital et al., 2002; Gendler-Shalev & Dromi, 2021). This is a Hebrew adaptation of the English CDI parental questionnaire (Fenson et al., 1994). It was recently adapted for Hebrew, validated, and normed by Gendler-Shalev and Dromi (2021). For each of 428 words, the parent is asked to indicate whether the infant understands the word, understands and says the word, or not mark anything if the infant does not say and does not understand the word. The original CDI has high internal reliability (.95-.96, Fenson et al., 1994), as does the adapted Hebrew version (.98, Maital et al., 2002). The original CDI has a high correlation with infants' performance on the One Word Picture Vocabulary Test (.79) and their mean length of utterance (Fenson et al., 1994). For Hebrew, the test was not validated against an existing measure (since such a measure was not available) but rather, age-related growth curves were shown to be similar to those in the original English version, and expected effects such as an advantage for girls, and an effect of birth order were also demonstrated (see Gendler-Shalev & Dromi, 2022).

Norms exist from 12 months of age, but for the sake of this study, Gendler-Shalev provided us with unpublished norms from 9 months of age. For 8-month-olds (12 infants), we used the 9-months quantiles for comprehension, but removed these children from the analysis for the production models, since, even at 9 months, infants in the 50^{th} quantile only produce 1 word, and it is thus unclear whether an infant who does not yet produce a single word is in the 10th or 40th quantile. Since 8-months-olds would reasonably produce even fewer words, we reasoned that it was uninformative whether an 8-month-old produced 1 word or none. Thus, the analysis of expressive vocabulary only included 81 infants. The online forms of the Hebrew CDI include some demographic questions, which we used to describe our sample's demographics in addition to our own questionnaire which we describe below.

Language-promoting Interactions. We developed this questionnaire based on a previous longitudinal study which included observations of 9- to-18-months-old infants (Alison & Clarke, 1973), as well as items borrowed from the StimQ questionnaire Parental Involvement in Developmental Advance subscale (Dreyer et al.,1996) such as: “Do you have opportunities, daily, to point at objects in the environment of the house and name them (such as point at a tree and say “tree”)?”. For each question the parent indicated whether the infant or themselves often act in this way (2 points), sometimes act in this way (1 point) or does not yet act in this way (0 points).

As mentioned above, there was some challenge with operationalizing the concept of language-promoting interactions. Interactions can either be initiated or led by the infant, or they can be initiated, led, or controlled by the parent. Given this complexity, we opted to develop a questionnaire which captures both types of behaviors. 11 items ask about the infant’s proactive behavior, such as “Does your child bring you books to read to her/him[1]?” and “Does your child attempt to draw your attention by throwing an object out of reach?”. 10 items ask about parental behaviors, such as “Do you have opportunities, daily, to point at objects in the environment of the house and name them (such as point at a tree and say “tree”)?” and “Do you teach your child the names of body parts while touching her/him and naming the body part (e.g., “here is your nose”)?”. Most of the items pertaining to parental behavior are *related* to items asking about infant behavior. For example, the infant-behavior item “When your child needs help, or wants an object that is out of reach, do they try to draw your attention to it in some way (e.g., by looking at it, vocalizing or pointing to the object)?” is followed by the parental-behavior item: “Do you tell the child in words what they asked for (for example, “did you want me to give you the pacifier?”)?”. Three items directly relate to an interaction (e.g., “Does your child come over to you when you call him/her?”), and the remaining two are “Does your child make sounds?” and “Does your child play with an object and explore it in different ways (e.g., banging on it or throwing it)?”.

See supplementary materials for the full questionnaire in the OSF link:
https://osf.io/hrmp6/?view_only=1248633dd1e943babdf316e4ed205191.

Demographic details. We asked about children’s date of birth, sex, maternal years of education, parents’ native languages, the percentage of time infants hear each language, the number of children in the family, birth order, week of gestation at birth, and birth weight.

Additional measures. We also asked parents about the age at which their child began sitting, standing, crawling and walking. This data was not analyzed but the number of sitting, standing, crawling, and walking infants, as well as the mean age at which they reached theses millstones are summarized in Table 1[2].

[1] The questionnaire was in Hebrew, which does not have a gender-neutral pronoun. Parents received a version of the questionnaire which fit their and their infant’s gender.

[2] We additionally collected the Availability of Learning Materials and Reading subscales of the StimQ (Dreyer, et al., 1996). The Availability of Learning Materials subscale of the StimQ produced a ceiling

Table 1. ***Participants' characteristics on all collected measures (N = 93)***

Measure	Range	Mean (SD) / median or mode were appropriate
Infant's sex	42% girls	
CDI filler's gender	94% mothers, 4% fathers, 2% both parents filled in the CDI	
Infant's age	8-18	12.4 (3.24)
Birth order	1-5	1.82 (0.97) Mode = 1 Median = 2
Maternal years of education	13-23	16.8 (1.39)
ASQ gross-motor scale	0-6	4.34 (1.68)
Language-promoting interactions questionnaire	7.5-33.5	24.75 (5.03)
CDI comprehension (number of words)	0-401	111.96 (104.33)
CDI comprehension (quantile)	10-90	42.45 (28.27) Median = 50
CDI production (number of words)	0-220	21.63 (37.21)
CDI production (quantile)	10-90	34.81 (29.06) Median = 25
StimQ (RD) reading scale	0-16	9.59 (3.97)
Age at which began sitting unsupported (N = 75)	5.5-11.5	7.6 (1.56)
Age at which began standing unsupported (N = 79)	5.5-14	8.89 (1.85)
Age at which began crawling (N = 84)	4.5-10.5	6.59 (1.63)
Age at which began walking (N = 36)	8.5-18	12.78 (1.94)
Duration sitting unsupported (N = 75)	0.11-13.68	5.85 (3.26)
Duration standing unsupported (N = 79)	0.1-13.68	4.47 (3.13)
Duration crawling (N = 84)	0.12-12.29	6.45 (3.45)
Duration walking (N = 36)	0.1-8.39	3.09 (1.76)

effect where all participants achieved the highest score, and was not used. The READ scale was finally not used as a control in the analyses, as there is no a priori reason for it to be related to motor development, only language development.

Note: The reason Ns differ from the total sample size for motor milestones' age and duration is that some children did not yet achieve these milestones, for example 8 out of 93 infants did not yet independently sit unsupported, resulting in N = 75.

Analysis Plan

For each model (CDI comprehension and production quantile separately), we first examined the relationship between motor development and language-promoting interactions with a linear model (the lm function). We then examined the relationship between language-promoting interactions and CDI quantile with the glmmTMB function (glmmTMB package, Brooks et al., 2017), and a beta family parameter (since the dependent variable is measured in quantiles), and then examined the relationship between motor development and CDI quantile with the glmmTMB function. For these models, we also calculated a Baysian approximation using Bayesian Information Criterion (BIC) values, relying on the R package bayestestR and the function bic_to_bf (Makowski et al., 2019). A BIC provides an approximation to a Bayesian hypothesis test, but does not require the specification of priors (see Wagenmakers, 2007). Finally, we ran a mediation analysis using the robmed package (Alfons et al., 2022) and the test_mediation function via bootstrapping (5000 interaction).

In all models, we statistically controlled for factors hypothesized to be related to both motor and language development (Wysocki et al., 2022): child's age and sex, birth order, and maternal education.

Results

Before examining our hypotheses, we descriptively present Pearson correlations between our variables in Figures 1 and 2. Infants' age was correlated with infants' ASQ gross-motor scale scores, their language-promoting interaction scores and StimQ parental reading scores. Their CDI comprehension quantiles were correlated with their ASQ gross-motor scale scores and StimQ parental reading scores. Their ASQ gross-motor scale scores were correlated with their CDI language production and comprehension quantiles, StimQ parental reading scores, language-promoting interactions score and their age. Their language-promoting interaction scores were correlated with CDI language production quantile, their ASQ gross-motor scale scores, age, maternal education and StimQ parental reading scores.

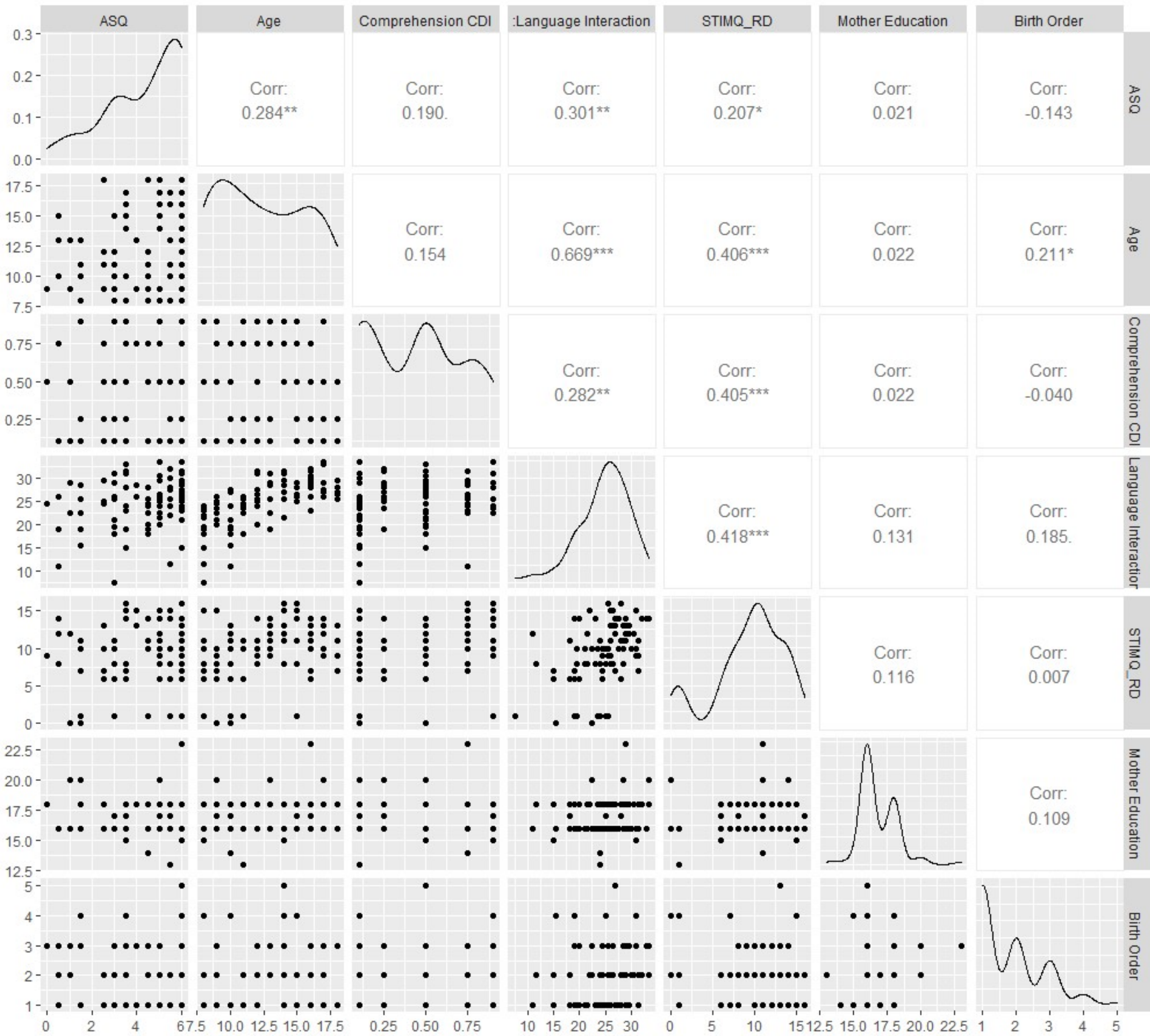

Figure 1: ***Relationship between all measured variables for the language comprehension sample. The diagonal shows density of the distribution of each of the variables. Panels below the diagonal show the scatter plot for the two variables involved (e.g., age and ASQ gross-motor subsection, first column). Those above the diagonal show the Pearson correlation for the two variables involved.***

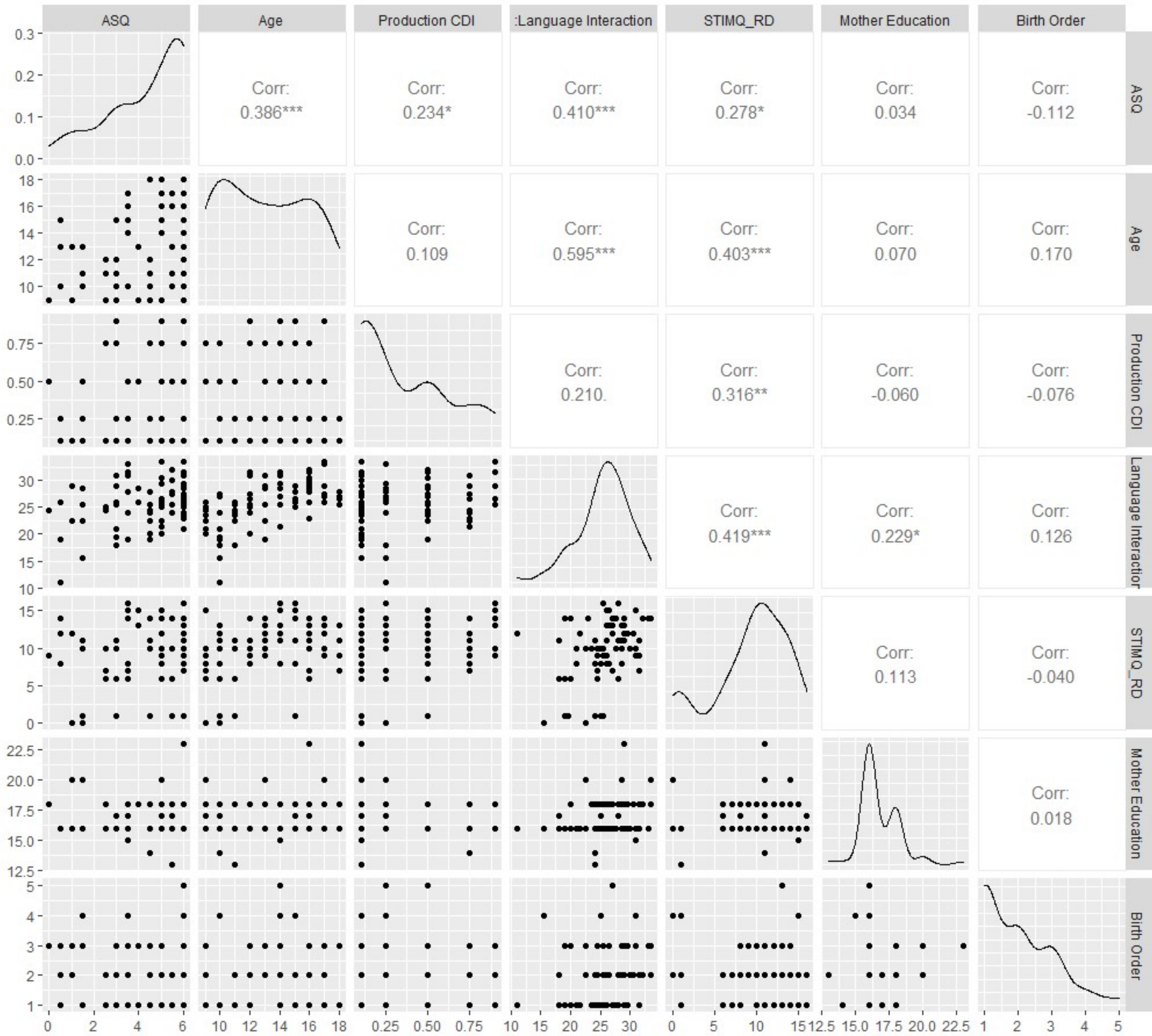

Figure 2: ***Relationship between all measured variables for the language production sample. The diagonal shows density of the distribution of each of the variables. Panels below the diagonal show the scatter plot for the two variables involved (e.g., age and ASQ gross-motor subsection, first column). Those above the diagonal show the Pearson correlation for the two variables involved.***

We next tested our hypotheses about the relationship between motor development, language-promoting interactions, and language development (CDI comprehension and production separately).

Motor development, language-promoting interactions and language comprehension (N = 93)

There was a significant relationship between language-promoting interactions scores and CDI comprehension quantiles, with anecdotal evidence for a relationship between the two in the Bayesian analysis (beta = 0.071, SE = 0.033, *p* = .029, BF = 1.212, see table 2). There was no significant relationship between ASQ gross-motor scale and language-promoting interactions, with anecdotal evidence against a relationship between the two in the Bayesian analysis (beta = 0.382, SE = 0.233, p = .104, BF = 0.442, see table 2). The relationship between ASQ gross-motor scale and CDI comprehension quantiles was not significant, and the Bayesian analysis showed moderate evidence against a relationship between the two (beta = 0.73, SE = 0.069, *p* = .289, BF = 0.187, see table 2).

Table 2. ***Summary statistics for the models testing the relationship between CDI comprehension quantiles, ASQ gross-motor scale and language-promoting interactions.***

Model 1: CDI by Interactions questionnaire	Estimate	Std. Error	z value	p
(Intercept)	-1.525	1.410	-1.081	.280
Language-promoting interactions questionnaire	0.071	0.033	2.189	.0286*
Age	-0.025	0.047	-0.531	.595
sex - Male	0.055	0.226	0.243	.808
Maternal education	-0.001	0.079	-0.018	.985
Birth order	-0.093	0.116	-0.803	.422

Model 2: Interactions questionnaire by ASQ	Estimate	Std. Error	z value	p
(Intercept)	4.470	4.774	0.936	.352
ASQ	0.382	0.233	1.642	.104
Age	0.942	0.126	7.503	< .0001***
sex - Male	0.614	0.778	0.789	.432
Maternal education	0.383	0.271	1.417	.160

Birth order	0.226	0.415	0.546	.587

Model 3: CDI by ASQ	Esti-mate	Std. Error	z value	p
(Intercept)	-1.231	1.393	-0.884	.377
ASQ	0.073	0.069	1.061	.289
Age	0.036	0.036	0.981	.327
sex - Male	0.077	0.227	0.338	.736
Maternal education	0.020	0.079	0.252	.801
Birth order	-0.064	0.121	-0.528	.597

Bootstrapped mediation analysis found that the point estimate of the total effect of the ASQ gross-motor scale on the CDI comprehension quantile was .032 (p = .21), the direct effect was .029 (p = .272), and the indirect effect was .004, thus, no mediated effect was attested (see Table 3).

Table 3. ***Summary statistics for the mediation analysis between the CDI comprehension quantiles and ASQ gross-motor scale, mediated by language-promoting interactions.***

Total effect of ASQ on CDI:	Data	Boot	Std. Error	Z value	*p*
	0.033	0.032	0.026	1.257	.209
Direct effect of ASQ on CDI:					
	0.029	0.027	0.025	1.093	.275
Indirect effect of ASQ on CDI though Language-promoting interactions questionnaire:					
	Data	Boot	95% CI Lower	95% CI Upper	
	0.004	0.005	-0.006	0.025	

Motor development, language-promoting interactions and language production (N = 81)

There was no significant relationship between language-promoting interactions scores and CDI production quantiles, with anecdotal evidence against a relationship between the two in the Bayesian analysis (beta = 0.056, SE = 0.035, p = .106, BF = 0.43, see Table 4). There was a significant relationship between ASQ gross-motor scale scores and language-promoting interactions scores, with anecdotal evidence for a relationship between the two in the Bayesian analysis (beta = 0.589, SE = 0.24, p = .017, BF = 2.62, see Table 4). The relationship between ASQ gross-motor scale and CDI production quantiles was not significant, with moderate evidence against a relationship between the two in the Bayesian analysis (beta = 0.098, SE = 0.072, p = .176, BF = 0.285, see Table 4).

Table 4. ***Summary statistics for the models testing the relationship between CDI production quantiles, ASQ gross-motor scale and language-promoting interactions.***

Model 1: CDI by Interactions questionnaire	Estimate	Std. Error	z value	*p*
(Intercept)	-0.684	1.387	0.493	.622
Language-promoting interactions questionnaire	0.056	0.035	1.614	.106
Age	0.007	0.051	0.140	.889
Sex - Male	-0.044	0.248	0.179	.858
Maternal education	-0.073	0.079	0.921	.357
Birth order	-0.090	0.118	0.762	.446
Model 2: Interactions questionnaire by ASQ	**Estimate**	**Std. Error**	**z value**	***p***
(Intercept)	3.241	4.816	0.673	.503
ASQ	0.589	0.240	2.454	.017 *
Age	-0.509	0.841	0.605	.547
Sex - Male	0.774	0.152	5.086	< 0.001 ***
Maternal education	0.570	0.271	2.102	.039 *
Birth order	0.347	0.399	0.871	.387
Model 3: CDI by ASQ	**Estimate**	**Std. Error**	**z value**	***p***
(Intercept)	-0.511	1.374	0.372	.710
ASQ	0.098	0.072	1.352	.176
Age	0.036	0.044	0.824	.410
Sex - Male	-0.093	0.248	0.377	.706
Maternal education	-0.048	0.078	0.619	.536

Birth order	-0.049	0.118	0.412	.681

Bootstrapped mediation analysis found that the point estimate of the total effect of the ASQ gross-motor scale on the CDI production quantile was .02 (p = .365), the direct effect was .016 (p = .43), and the indirect effect was .002 - thus, no mediated effect was attested (see Table 5).

Table 5. ***Summary statistics for the mediation analysis between the CDI production quantiles and ASQ gross-motor scale, mediated by language-promoting interactions.***

Total effect of ASQ on CDI:	Data	Boot	Std. Error	Z value	*p*
	0.018	0.02	0.022	0.892	.372
Direct effect of ASQ on CDI:					
	0.016	0.017	0.022	0.772	.44
Indirect effect of ASQ on CDI though Language-promoting interactions questionnaire:					
	Data	Boot	95% CI Lower	95% CI Upper	
	0.002	0.002	-0.004	0.025	

Discussion

The present study examined the theory that the relationship between motor development and language development is mediated by language-promoting interactions. According to Iverson (2010, 2021), motor development helps children have more complex and self-initiated interactions with their environment, in ways that encourage parents to produce quality language-promoting input. For example, a walking infant may carry their favorite toy to their caretaker, encouraging joint attention around an object of their interest. This makes the infant a proactive, and not just an active, partner in these interactions. Such interactions, in turn, have been shown to support language development (Brooks & Meltzoff, 2005; Morales et al., 2000).

Here, we tested this suggestion by asking parents about their infant's motor development, language development, and their interactions with their infants. We found that, in comprehension, there was no significant direct or mediated relationship between motor and language development. However, there was a significant relationship between language-promoting interactions and language comprehension as previously found (e.g., Ramírez-Esparza, et al., 2014). We found no relationship between motor development and language-promoting interactions.

The picture was slightly different for children's production scores. Here, motor development was related to language-promoting interactions, but there was no relationship between language-promoting interactions and language production, nor a direct or mediated relation between motor development and language development.

Note that, unlike their vocabulary scores, which differ in the comprehension and production analysis, infants' motor and language-promoting interaction scores are the same in both models. However, the production sample is a subsample of the comprehension sample and it therefore smaller and biased towards older ages in the language-production analysis - given that 8-month-olds did not have production quantiles, but did have comprehension quantiles. We therefore do not want to give too much weight to the fact that we found a significant effect of motor development on language-promoting interactions in the production but not comprehension analysis. The fact we only find this effect in a subsample of our study might be because the effect only exists in older children, but we believe it is likely just due to chance. It is, however, also possible that this effect only exists in older infants, who are more likely to have made the transition to walking, as will be discussed below.

Since most of our results, and especially the direct relationship between motor and language development, were not significant, we should consider the possibility that such a relationship indeed does not exist. The first possible reason could be that one crucial tipping point in the co-development of language and motor ability is walking. This milestone has been found to be particularly related to gesture growth, gesture and vocalization coordination and contingent talk by parents (Schneider & Iverson, 2021; West & Iverson, 2020). Schneider & Iverson (2021) found infants were more likely to hear caregiver language and gestures that either requested or described movement or provided information about objects - after they made the transition to walking. Moreover, they found an effect of infants' real-time behavior, such that infants were more likely to hear language from their caregivers when they moved while upright than when they crawled. These parental behaviors are most likely captured by our language-promoting interactions measure. Other researchers also focused on walking onset and experience and their relation to productive and receptive vocabulary. For example, Walle (2016) found that infant initiation of joint engagement and following of the parent's joint engagement cues increased as infants gained walking experience (again, these behaviors should be captured by the measure we developed). He also found that walking experience predicted infants' receptive and productive language. Our sample only included 36 infants who could already walk, as opposed to 57 who could not yet walk. Future studies should focus more on the transition to walking.

We should also consider the possibility of a meaningful null result, one that signifies that a relationship between language and motor development is not statistically reliable. However, this goes against much of the literature today, on both typically developing (see Gonzalez et al., 2019; and Leonard & Hill, 2014 for systematic reviews), and disabled children (e.g.,Gaines & Missiuna, 2007; Ross et al., 2018). While these previous findings might also represent a biased literature base, we would be very wary to suggest so, given their consistency across different populations. We find it more likely that the limitations of the current study (a small sample size, exclusive use of parental reports from the same parent, cross-sectional design, little focus on the transition to walking described above) prevented us from finding an effect of motor skills on language skills.

As for a lack of significant mediation by language-promoting interactions, it might be due to the same limitations that prevented us from finding a significant relation between motor and language development. It could also be that the measure of language-promoting interactions we developed was not valid or not sensitive enough to individual differences in behavior. Indeed, we described in the introduction the challenge of developing a measure that would capture both parent-initiated and child-initiated interactions, as well as parental responses to child-initiated interactions. It could also be that parental reports are not a good way to assess interactions, as parents might be driven by social desirability to report behaviors which sound supportive or beneficial for child development. Indeed, this might be the reason studies of parental interactions with their children tend to use observational methods (e.g., Alison & Clarke, 1973, on which we based a portion of our questionnaire). It might be worthwhile to test the same hypothesis with observational methods (for both motor development and interactions), however, this would most probably serve to lower even further the sample size.

Our findings do not lend support to the hypothesis that language-promoting interactions mediate the relationship between motor and language development. However, it would be wrong to rely on them to claim the opposite – most of our analyses did not find significant results, but Bayesian analysis shows them to be inconclusive rather than supporting the null hypothesis. We therefore suggest the main conclusion from this study should be that there is need for further research, especially research tackling the main limitations of the current study described above. In addition, the questionnaire we developed has not been validated. However, we hope others will use it, validate, and improve it for use in the study of motor development, language development, and the relationship between the two.

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Data, code and materials availability statement

The data and code are available on the OSF: https://osf.io/hrmp6/?view_only=1248633dd1e943babdf316e4ed205191.

As for materials, the language-promoting interactions questionnaire we developed, as well as the StimQ, are available on the link above. The Hebrew Web Communicative Development Inventory - CDI is available on WordBank, though note that currently the norms are not updated, and no norms for children under 12 months were yet uploaded: http://wordbank.stanford.edu/data?name=vocab_norms

The editor approved an exemption (18th January 2023) to materials sharing for the Ages and Stages Questionnaire, which is subject to copyright. A sample questionnaire is available on the ASQ website: https://agesandstages.com/wp-content/uploads/2015/02/asq-3-48-month-sample.pdf

Ethics statement

Ethics approval was obtained from the ethics committee of the University of Haifa, School of Psychological Sciences. All participants gave informed written consent before taking part in the study.

Authorship and Contributorship Statement

SBO and NH conceived of the study, designed the study and wrote the first draft of the manuscript. SBO collected the data. NH analysed the data. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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