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ORIGINAL PAPER

From Using Tools to Using Language in Infant Siblings of Children with Autism

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Abstract
Forty-one high-risk infants (HR) with an older sibling with autism spectrum disorder (ASD) were observed longitudinally at 10, 12, 18 and 24 months of age during a tool use task in a play-like scenario. Changes in grasp types and functional actions produced with a spoon were assessed during elicited tool use. Outcome and vocabulary measures were available at 36 months, distinguishing: 11 HR-ASD, 15 HR-language delay and 15 HR-no delay. Fewer HR-ASD infants produced grasp types facilitating spoon use at 24 months and functional actions at 10 months than HR-no delay. Production of functional actions in HR infants at 10 months predicted word comprehension at 12 months and word production at 24 and 36 months.

Keywords Autism · High-risk siblings · Grasping · Functional actions · Tool use · Language

Introduction

Autism spectrum disorders (ASDs) are characterized by deficits in communication and the presence of repetitive and stereotyped behaviors (DSM-V, American Psychological Association 2013). However, recent studies underscore the presence of additional delays in purposeful actions, such as object exploration and functional actions, in children with ASD beginning in infancy, with possible cascading effects on later language. In particular, research has highlighted delays in fine-motor skills and purposeful actions (e.g., drinking from a cup) measured using parent interviews or dedicated standardized tests (e.g., Communication and Symbolic Behavior Scales Developmental Profile) at 18 and 24 months in infants at heightened risk for ASD (HR infants; i.e., younger siblings of children with ASD) who received an ASD diagnosis at 36 months (Landa and Garrett-Mayer 2006; LeBarton and Iverson 2013) and specific delays in frequency of object grasping (e.g., rattles) in HR infants compared to typically developing peers (Bhat et al. 2009; Libertus et al. 2014). Differences in developmental patterns among HR infants have also been found in skills involved in object exploration (i.e., mouthing, dropping, object manipulation, transfer and rotation) using structured experimental tasks relying on different object sets (e.g., rattles, small balls, etc.) (Koterba et al. 2014; Kaur et al. 2015; Ozonoff et al. 2008). These delays have been linked with difficulties building simple sequences of functional actions with toys in play contexts (i.e., functional play) in infants and toddlers with ASD compared to both typically developing controls and children with other developmental delays (e.g., Down syndrome) (Christensen et al. 2010; Landa et al. 2007; Williams et al. 2001). In light of results indicating a relation between functional play and communication in typical development (Bates et al. 1979; Iverson 2010; Lifter and Bloom 1989), several studies have suggested that early delays in motor skills or functional actions during play may

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impact later language development in ASD (Bhat et al. 2011, 2012; Christensen et al. 2010; Gernsbacher et al. 2008; Iverson and Wozniak 2007; Landa et al. 2007; LeBarton and Iverson 2013; Lewis 2003; Linkenauger et al. 2012; Stone and Yoder 2001; Ungerer and Sigman 1981; Williams et al. 2001). Different studies have begun to address how/why motor and functional actions with objects may impact later language development in infants with ASD. Some studies highlight how infants require a full repertoire of movement behaviors to engage in social communication (Bhat et al. 2012). Furthermore, by engaging in motor and functional object exploration, typically developing infants also increase their ability to detect salient object characteristics, as well as develop categorization and joint attention skills, which in turn support vocabulary development (Williams et al. 1999, 2001; Smith 2013). Research has also highlighted that in children with ASD, manual-motor skills at 24 months are predictive of expressive language at 48 months (Stone and Yoder 2001), and that fine motor skills at 24 months predict speech fluency later in life (Gernsbacher et al. 2008). Finally, according to Elizabeth Bates' theory on symbolic development, as we trace the emergence of linguistic symbols in infancy we find that this phenomenon is made out of other, older and quite independently developing parts. Among these, functional play schemes (e.g., putting empty cups or silverware to the lips) with objects play a very relevant role. Functional play schemes allow infants to practice action sequences which, later detached from the 'games' in which they emerged, appear in gestural and/or vocal modalities (e.g., bringing an empty hand to the lips in the shape of a cup or a spoon, saying 'yum yum'), leading to symbolic and flexible use of previously acquired skills (Bates et al. 1979).

In fact, one of the main motives behind growing research interest in atypical motor skills in HR infants is their utility in predicting outcomes in communication domains. While deficits in both verbal and nonverbal communication have proven hard to detect before 12 months of age, delays in different levels of purposeful actions with objects (e.g., reaching, grasping, holding and transferring objects) and motor skills have been reported as some of the earliest signs of atypical developmental trajectories in younger HR infants (Elsabbagh and Johnson 2010; Landa et al. 2013; Libertus and Landa 2014; Rogers 2009). Despite the increasing number of studies on purposeful actions with objects in HR infants, there are currently several gaps in the literature. First, studies of specific actions (e.g., grasping), have mostly provided quantitative data (i.e., presence or frequency of grasping), but not fine-grained qualitative analyses (e.g., *how* objects are grasped and explored). Possibly this is due to the lack of a taxonomy for the classification of grasp types in infancy proven to be applicable to HR infants. This is somewhat surprising considering the relevance of grasping and efficiently using tools in shaping our understanding of the emergence of purposeful actions and acquiring autonomy in everyday tasks (Bates et al. 1979; Connolly and Dalgleish 1989; Lockman 2000). Furthermore, assessments of functional actions in HR infants have been limited to play or everyday scenarios considering multiple objects and actions with varying levels of difficulty, making it hard to clearly parse out functional acts and trace their emergence in time. Finally, no study to date has analyzed how functional action production may vary across different diagnostic outcomes nor the relationship between functional action production and later language in HR infants, despite the fact that links between functional actions and language are currently a major area of research interest in typical development (Bhat et al. 2011; Christensen et al. 2010).

Grasping, Functional Actions and Language in Typically Developing Infants

In typical development, tool use relies heavily on grasping skills and perception–action routines used in object exploration (Kahrs et al. 2013; Lockman 2000). Initially, tools are explored just like all other objects through multimodal activities (e.g., grasping, mouthing, dropping, object transfer and rotation, and visual exploration; Rochat 1989; Ruff et al. 1992). However, gradually infants learn not only to detect tool affordances, but also to relate them to the manual effector system as well as other objects and task spaces in order to execute functional actions (Lockman 2000). For example, Gesell et al. describe how, at 9 months, infants begin grasping a spoon and exploring its affordances (e.g., dropping or banging the spoon), by 10 months, they are able to place a spoon near a bowl without relating the two objects functionally (i.e., as container and contained), while around 13 months functional actions emerge (i.e., using a spoon as a tool to be inserted in a bowl) (Gesell and Ilg 1937; Gesell et al. 1934).

Qualitative data on grasping development has proven essential to understand the emergence of functional actions with tools in infancy. In fact, it offers relevant insight on trial and error behaviors and how infants dynamically learn to adapt the manual effector system to specific tools and environmental constraints (Newell 1986; Newell et al. 1990; Lee et al. 2006). While at 6 months infants mostly produce basic grasp types using the palm of the hand (i.e., palmar grips), between 7 and 8 months objects start to be shifted towards the radial side of the hand with the emergence of thumb opposition. Further development of thumb opposition between 9 and 13 months leads to objects being held with the tip of the fingers while projecting from the hand (i.e. precision grips) (Connolly and Elliott 1972; Halverson 1943; Napier 1956). This process is strongly shaped by the objects or tools that infants encounter during development and the context of their use (Newell et al. 1990; Newell 1986).

Connolly and Dalgleish (1989) provide a detailed account of spoon grasp development between 11 and 23 months of age, using a fine-grained classification of grasp types along four main dimensions: grip type, thumb opposition, grip strength and object projection. They also distinguish grasp types which facilitate or hinder the production of subsequent functional actions. This analysis shows how infants initially produce many different grasp types, which diminish in variety over time: older children tending progressively to select grasp types facilitating functional actions over grasp types hindering them (Connolly and Dalgleish 1989). McCarty et al. (1999) replicated these findings in a study on spoon grasping in infants between 9 and 19 months of age. Taken together, these data suggest that gradual emergence of grasp types and tool use in infancy is not only important per se, but also because it changes infants' experiences with objects and people, by creating opportunities to practice functional object use within different contexts, a relevant skill for general communicative development and language acquisition (Bates et al. 1979; Iverson 2010). This process is often observed in studies dedicated to the development of functional play in infancy and toddlerhood.

Several authors stress the existence of a relation between the development of functional play and language (Bates et al. 1979; Fein 1979; Lifter and Bloom 1989; Sinclair 1970; Vygotsky 1967). For example, Lifter and Bloom (1989) analyzed the relation between object knowledge and language in infants between 9 and 26 months of age in spontaneous play. The authors used object sets in which individual items or tools could be used together in actions with different levels of complexity. For example, infants could either reconstruct a relation between objects identical to the one in which these objects were originally presented to them (i.e. placing a spoon on its silverware tray), impose a new but generic arrangement (i.e. placing a spoon onto a flat surface), or impose a new and specific relation between objects (i.e. using a spoon to feed a doll). Interestingly, this developmental progression in functional action complexity was related to achievements in language development rather than chronological age. In particular, during the first words phase infants started to impose new, but generic arrangements, while during the vocabulary spurt infants produced new and specific relations between objects (Lifter and Bloom 1989; see also Iverson 2010 for a more extended discussion).

Further evidence of a relationship between functional actions and language, in particular word comprehension, has emerged in studies using the MacArthur-Bates Communicative Development Inventories (CDIs), i.e. parent questionnaires assessing children's action and gesture production as well as word comprehension, word production and early grammatical development between 8 and 36 months (Fenson et al. 2007). Two separate studies have shown that between 10 and 18 months of age specific functional actions with objects precede the production of the corresponding symbolic gesture or word (Capirci et al. 2005; Caselli et al. 2012). Bavin et al. (2008) used the CDIs in a large sample study to determine whether actions with objects at 8 months predicted word comprehension and production at 12 months and word production at 24 months. Results showed significant correlations between these measures. However, correlations were higher between actions with objects at 8 months and words comprehended at 12 months than words produced at either 12 or 24 months (Bavin et al. 2008). In sum, studies of typical development highlight that fine-grained analyses of grasp types and functional actions not only provide relevant information about the development of infants' fine-motor skills and ability to use objects in a functional way, but also offer new data about the relation between motor skills and language acquisition (Iverson 2010).

Grasping, Functional Actions and Language in HR Infants

Results from studies on grasping in HR infants to date seem to point toward a common finding: HR infants show similar, but delayed, grasping skills compared to typically developing infants, a phenomenon best captured by longitudinal approaches. Libertus et al. (2014) analyzed toy grasping in HR and LR infants (LR; i.e., infants without a previous family history of ASD) at 6 and 10 months in a prospective study using a naturalistic free-play context. Results showed reduced frequency of grasping in HR infants at 6 months, but not at 10 months, possibly indicating presence of a delay attenuating with age (Libertus et al. 2014). Similarly, Kaur et al. (2015) found less grasping and mouthing of toys at 6 months in HR infants compared to LR controls, this difference was no longer present by 10 months. These results are in line with other studies of object exploration in HR infants considering other exploratory strategies (Baranek 1999; Koterba et al. 2014; Ozonoff et al. 2008), but studies of grasping skills in HR infants have typically considered very young infants and only provided quantitative information (i.e., grasp frequency). Longitudinal data on grasp *type* development at older ages, comparable to that present in studies on tool use in typical development, is not available. Furthermore, existing studies mostly report data on comparisons between HR vs. LR groups, but lack diagnostic outcomes. Therefore, in the present study we focused on analyzing changes in grasp types between HR infants with different diagnostic outcomes, and also propose a taxonomy for the classification of grasp types derived from the works of Connolly and Dalgleish (1989) and McCarty et al. (1999) on typically developing infants in order to provide comparable data in HR infants.

To our knowledge, this is the first study specifically designed to study the development of functional actions in HR infants. Parents and clinicians report that children with ASD display unusual and often disruptive spoon use at mealtime in infancy and early childhood (Asperger 1944; Park 1983; Ungerer and Sigman 1981; Williams et al. 2005). Mulligan and White (2012) compared motor behaviors of HR infants and LR controls at 12 months during play and feeding with a spoon, and found differences during play, but not during feeding (Mulligan and White 2012). They state that their findings may have been limited by considering only one time point, by the fact that spoon-feeding was mainly based on a caregiver-led routine, and by the fact that differences in behavior were not analyzed in relation to diagnostic outcome (i.e., out of the 13 HR infants considered in this study only 4 received an ASD diagnosis; Mulligan and White 2012). Other studies dedicated to play behaviors in HR infants, including functional actions (e.g., putting a toy spoon in a toy cup and stirring), indicate delays at 18 months in HR infants who later receive an ASD diagnosis compared to LR controls, which attenuate with age (i.e., by 24 months) (Christensen et al. 2010; Campbell et al. 2016). However, some caution should be exercised when evaluating production of functional actions in HR infants based on studies of play scenarios, which usually include multiple toys, some of which may be easier or harder to use, and frequently differ in their classification of functional actions (Landa et al. 2007). Taken together these studies suggest that a dedicated analysis of functional action production in HR infants is still needed to better understand documented delays. Consequently, in our study we specifically analyzed functional action production in HR infants considering: multiple time points and diagnostic outcomes, and relying on functional tool use within a play-like scenario rather than in the presence of food to avoid confounds due to parent-led routine effects.

Finally, a growing body of research has highlighted delays in communication and language in infant siblings of children with ASD (Cassel et al. 2007; Yirmiya et al. 2006a; Gamliel et al. 2007), which have been linked to purposeful actions acquisition. For example, studies considering gross-motor skills in HR infants suggest that detected differences in specific skills (e.g., independent sitting, rhythmic arm movements, postural control) may lead to reduced object exploration and play, as well as fewer opportunities for social interaction and communication, with cascading effects on language development (Bhat et al. 2011, 2012; Iverson and Wozniak 2007; Ozonoff et al. 2008). However, only a few studies have considered the relationship between purposeful actions and language in HR infants. These studies highlight that in infant and toddlers with ASD, reduced manual-motor skills, motor imitation, and functional actions between 6 and 24 months impact later speech fluency and expressive language (Gernsbacher et al. 2008; LeBarton and Iverson 2013; Stone and Yoder 2001). This suggests not only that the relationship between functional actions and language described above in typical development also exists in HR infants, but also that differences in the production of manual functional actions as early as 12 months may have cascading effects on language. A first step towards a better understanding of comparable links between functional actions and language in HR infants may be made by considering similar age groups and comparable language measures to the ones present in the literature on typical development while controlling for cognitive ability.

Summing up, the aims of the present study are to extend existing literature on HR infants by: (1) analyzing the number of infants producing specific grasp types as well as longitudinal changes in the types of grasps infants used from 10 to 24 months; (2) to provide a longitudinal assessment of the emergence of functional actions in HR infants considering a familiar tool (i.e., a spoon) within a simple play scenario; and (3) to evaluate whether functional action production or lack thereof may vary across diagnostic outcomes (i.e., infants receiving an ASD diagnosis, infants with language delay, and infants with no delay at 36 months) and predict later language development in HR infants. Based on previous literature, our hypotheses were: (1) that considering HR infants from 10 months onwards would allow for sufficient variability in grasp types and that while similar changes would emerge to the ones observed in typical development (i.e., infants tending to progressively select grasp types facilitating functional actions over grasp types hindering them), this pattern may be delayed or more irregular in HR infants; (2) that infants later diagnosed with ASD would be less likely to produce functional actions by 18 months, but that this difference would diminish at later ages, in accordance with previous studies focusing on functional actions during play in HR infants (Christensen et al. 2010; Campbell et al. 2016); and (3) that functional acts would predict vocabulary at later ages in HR infants, in particular that actions with objects at 10 months would be better predictors of word comprehension at 12 months than word production at later stages (Bavin et al. 2008).

Methods

Participants

A total of 41 HR infants (25 male) with an older full biological sibling with ASD participated in the present study. Infants were drawn from a larger longitudinal study investigating the early development of HR infants (e.g., LeBarton and Iverson 2013). Families were recruited through the Autism Research Program at the University of Pittsburgh, parent support organizations, local agencies, and schools serving families of children with ASD. Prior to the first ancillary study visit, parents of infants signed an informed consent form giving permission for their child's participation in the study. The University of Pittsburgh Institutional Review Board approved all study procedures. Prior to each HR infant's enrollment, the Autism Diagnostic Observation Schedule (ADOS-G; Lord et al. 2000) was administered to their older sibling by a trained clinician to confirm diagnosis. Older siblings had to score above the threshold for Autism on the ADOS in order for infants to be eligible for inclusion in the study. All HR infants were full-term, from uncomplicated pregnancies and deliveries, and came from English-speaking homes. Sample demographics are presented in Table 1. As can be seen in the table, participants were primarily Caucasian and the vast majority of parents had attended college or had a graduate-level education.

Procedure

As part of the larger longitudinal study, all HR infants were observed monthly at home with a primary caregiver for approximately 30–45 min at regular intervals from 5 to 14 months, and again at 18, 24, and 36 months. In the present study we focus on a small portion of video data collected using the Early Social-Communication Scales (ESCS, Mundy et al. 1996) at the 10, 12, 18 and 24 month visits. All observations occurred within 3 days of the monthly anniversary of the infant's birth and at times when the parents thought the infants would be most alert and playful. All home visits were video- and audio-recorded.

Table 1 Sample demographics

	n = 41
Sex	
Male (%)	25 (61%)
Racial or ethnic minority (%)	5[a] (12%)
Mean age for mothers (SD)	34.07 (3.82)
Mean age for fathers (SD)	36.76 (4.39)
Maternal education	
Graduate of professional school (%)	17 (41%)
Some college or college degree (%)	20 (49%)
High school (%)	4 (10%)
Paternal education	
Graduate of professional school (%)	13 (32%)
Some college or college degree (%)	24 (58%)
High school (%)	4 (10%)
Mean paternal occupational prestige (SD)[b]	54.55 (16.36)

[a]Two infants were identified as Hispanic/Latino, one as Mixed Race (White and Asian), one as Asian, and one as Black or African American

[b]Nakao–Treas occupational prestige scores (Nakao and Treas 1994). Paternal occupation information was not available in 2 cases

The ESCS is a videotaped structured observation that is typically used to measure individual differences in nonverbal communication skills in children between 8 and 30 months of age. For the purpose of the present study we focused on the spoon and bowl item. The infant is presented with a bowl and a spoon while sitting or standing at a table in a supported position, and is allowed to spontaneously interact with these objects. A sample procedure is shown in Fig. 1.

Data were excluded if infants missed the entire visit, did not have the ESCS administered, did not have the spoon and bowl task administered within the ESCS, or had very poor video quality that precluded coding. Codable data were available for 94.5% (155/164) of videos.

Measures

The MacArthur-Bates Communicative Development Inventories (CDIs) (Fenson et al. 2007) are valid and reliable measures used across many languages and cultures in children with both typical and atypical development (Charman et al. 2003; Dale et al. 1989; Fenson et al. 1994; Luyster et al. 2007; Miller et al. 1995; Mitchell et al. 2006; Thal et al. 1999). The CDIs include: the CDI Words and Gestures (CDI-WG, 8- to 16-months-olds), which generates scores for vocabulary comprehension and production, the CDI Words and Sentences (CDI-WS, 16- to 30-month-olds), which yields scores for a number of aspects of grammatical development, including vocabulary comprehension and production, and the CDI-III (30–37 months-olds) also measuring vocabulary production. Parents of HR infants were asked to complete the CDI-WG at the 12 month visit, the CDI-WS at the 18 and 24 month visits, and the CDI-III at the 36 month visit.

The Mullen Scales of Early Learning (MSEL; Mullen 1995) is a standardized developmental assessment that provides a comprehensive measure of general cognitive functioning from birth to 68 months of age. It measures skills in Gross Motor, Fine Motor, Visual Reception, Expressive Language, and Receptive Language. Raw scores for these five domains are converted to T scores with mean of 50 and standard deviation of 10. Scores can also be combined to produce an Early Learning Composite (ELC; M = 100, SD = 15), which is considered a measure of overall cognitive functioning (Mullen 1995). The MSEL was administered at the 12, 18, 24, and 36 month follow-up visits for all HR infants.

Outcome Classification

Based on the ADOS-G at 36 months and standardized language measures at 18, 24, and 36 months, HR infants were classified into one of three groups: high-risk infants without ASD or language delay (HR-ND, $n = 15$, 7 males), high-risk

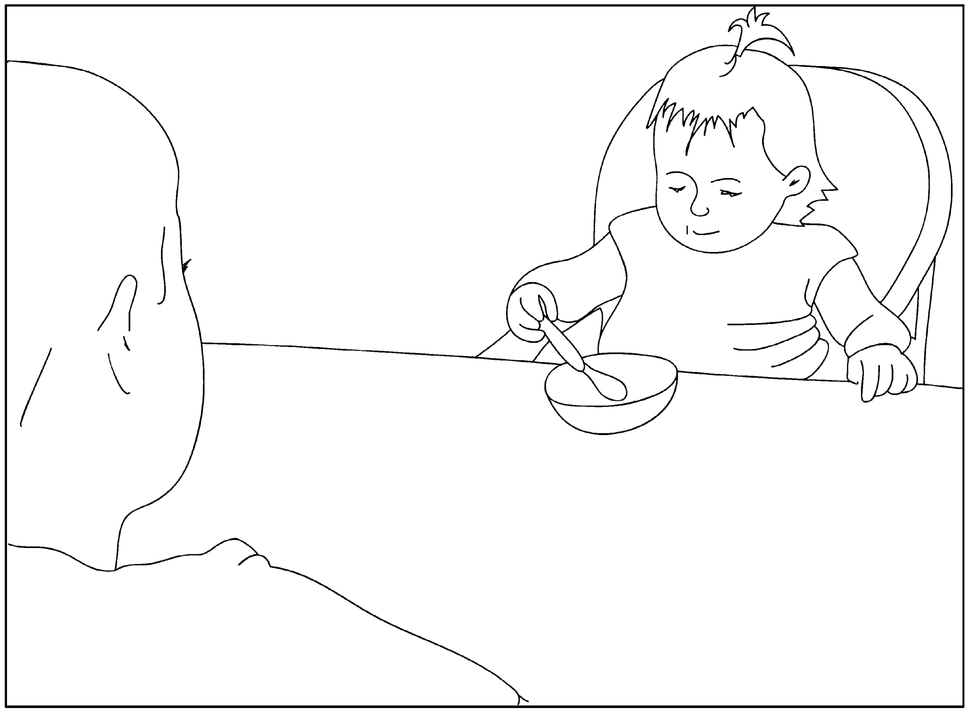

Fig. 1 Sample procedure for the spoon and bowl task within the ESCS

infants showing language delay, but not ASD (HR-LD, $n=15$, 10 males) and high-risk infants with autism or ASD diagnosis (HR-ASD, $n=11$, 8 males).

All infants were assessed for ASD by a clinician blind to study data at 36 months during a separate lab visit. Diagnoses were made based on administration of the ADOS, DSM-IV-TR criteria, and clinical best estimate.

To be categorized as HR LD, infants had to meet one of the following criteria and not receive a diagnosis of ASD: (1) Standardized scores on the CDI-WS and CDI-III at or below the 10th percentile at *more than one* time point between 18 and 36 months (e.g., Gershkoff-Stowe et al. 1997; Heilmann et al. 2005; Robertson and Weismer 1999; Weismer and Evans 2002); and/or (2) Standardized scores on the CDI-III at or below the 10th percentile *and* standardized scores on the Receptive and/or Expressive subscales of the MSEL equal to or greater than 1.5 standard deviations below the mean at 36 months (e.g., Landa and Garrett-Mayer 2006; Ozonoff et al. 2010).

Infants classified as HR-ND did not meet any of the above criteria for ASD or LD. Table 2 displays 36 month Mullen, CDI, and ADOS severity scores, a standardized metric of severity of ASD-specific features ranging from 1 to 10 (with 1 = no ASD features and 10 = severe ASD symptoms; Gotham et al. 2009), for infants in each outcome group.

Table 2 Standardized scores for HR-ND, HR-LD, and HR-ASD infants at 36 months

	HR-ND		HR-LD		HRASD	
	Mean	SD	Mean	SD	Mean	SD
Mullen ELC score 36 months	113.53[a]	19.72	97.00[b]	13.66	67.57[c]	15.77
Mullen visual reception T-score 36 months	60.80[a]	17.26	54.33[a]	13.68	31.13[b]	14.13
Mullen receptive language T-score 36 months	54.93[a]	10.69	46.20[a]	8.66	29.13[b]	10.96
Mullen expressive language T-score 36 months	59.27[a]	8.92	52.67[a]	6.10	31.44[b]	11.94
Mullen fine motor T-score 36 months	52.07[a]	15.92	40.13[b]	11.33	27.89[b]	7.56
CDI-III words produced raw score 36 months	61.29[a]	16.10	42.33[b]	13.42	12.10[c]	14.15
ADOS severity score 36 months	1.64[a]	1.15	1.93[a]	1.21	5.73[b]	1.42

ELC early learning composite, *HR* high risk, *ND* no diagnosis, *LD* language delayed, *ASD* autism spectrum disorder

Values in the same row not sharing the same superscript are significantly different at $p<.05$ using ANOVA with Bonferonni corrected post-hoc

Coding

Infants' behavior during the ESCS spoon and bowl task was coded using a time-linked annotation program (ELAN; Brugman et al. 2004) allowing annotation and characterization of data from a video source on a moment-to-moment basis. To control for consistency in task administration, the following variables were coded:

Task Duration

Overall duration of the spoon and bowl task within the ESCS began after presentation of the spoon and bowl by the experimenter and upon any movement of the child's hand towards the spoon (i.e., start of reaching). It ended when the spoon was no longer in contact with the child's hand (e.g., due to release or dropping) or when the experimenter's hand touched the spoon, the bowl or the child to remove one or both of these objects.

Infant Posture

Infants' overall posture during the spoon and bowl task was coded as sitting (i.e., if the infant sat on the caregiver's lab or independently supported on a chair) or standing (i.e., if the child was standing on the caregiver's lap or on the floor next to the table).

Spoon Presentation

Mode of presentation (i.e., if the spoon was moving or static when the child began reaching for it) was also coded for all trials. Given that the ESCS test occurred in an unstructured environment, the spoon was not always static at the moment the child reached for and grasped it. We controlled for this aspect by distinguishing cases in which the spoon was static at the moment of presentation (e.g., positioned on the table top or in the bowl, but not moving) or moving at the time of presentation (dynamic; e.g., the experimenter is moving the bowl with the spoon in it toward the child as the child reaches for it) (see also Newell and McDonald 1997 for a similar distinction and its the relevance in coding infant prehension). Out of the 155 presentations coded in this study, only 21 (13.5%) had a dynamic presentation.

Spoon Placement

Due to the semi-structured nature of the ESCS the spoon could be presented to the infant in different ways. Therefore, location (i.e., if the spoon was on the table or in the bowl) and orientation (i.e., how the spoon was oriented in relation to the child) were coded leading to eight possible combinations or spoon placements. However, as some combinations of location and orientation occurred more rarely than others, we decided to collapse spoon placements that only rarely occurred together for the purpose of simplifying results presentations, obtaining five possible spoon placements (see Fig. 2).

To measure production of grasping, grasp types and production of functional actions the following variables were coded:

Grasp Production

Presence of a spoon grasp was coded in each case in which an infant reached for the spoon and grasped it. Spoon grasp

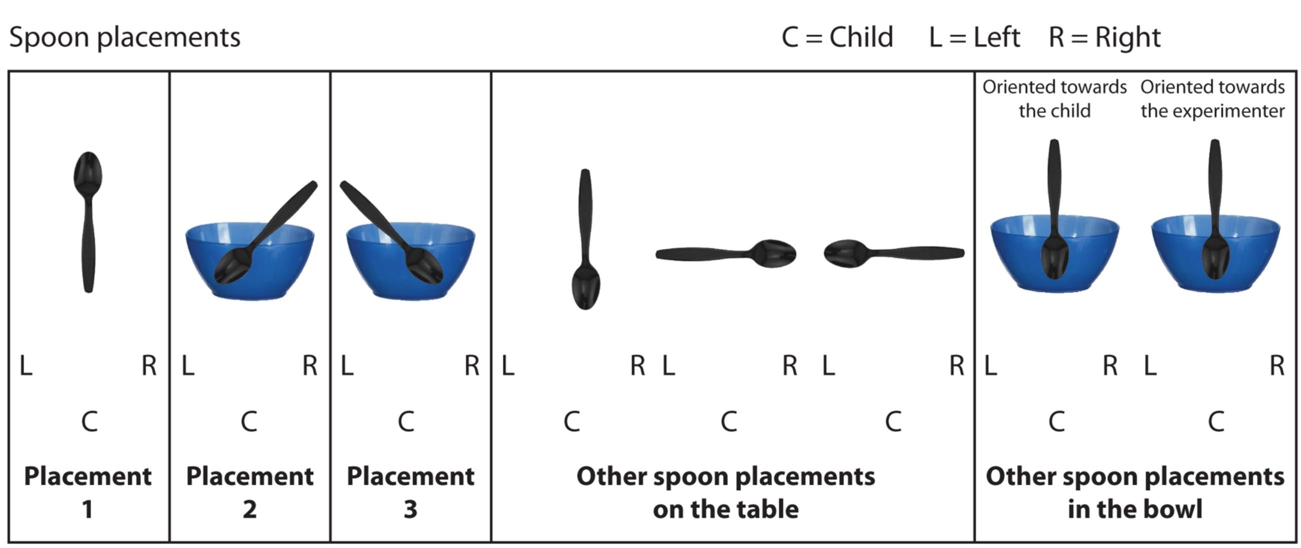

Fig. 2 Possible spoon orientations at start of the spoon and bowl task. *C* child, *L* child's left, *R* child's right

was considered absent when: the child did not produce a spoon grasp during the entire duration of the task, the child attempted to grasp the spoon, but failed to do so (e.g. only touched or fingered the spoon), or the child only grasped the bowl.

Grasp Type

In all cases in which infants produced a spoon grasp, grip patterns were defined in terms of the anatomical configurations of the hand, using four dimensions:

(1) Hand or hands used: we coded whether the spoon was grasped with one hand or bimanually.
(2) Object affordance: in all grasps performed with one hand, we coded whether the spoon was grasped from the handle, with the bowl of the spoon projecting from the hand, or from the bowl, with the handle projecting from the hand. Grasps of the latter type were all classified as head-end grasps. See also McCarty et al. (2001) for a similar classification in children's spoon grasps.
(3) Grip type: all one-handed grasps of the spoon's handle were classified based on whether the grip involved holding the spoon in the palm of the hand (i.e., palmar grip) or only the digits were involved (i.e., digital grip) (see also Napier 1956; Halverson 1943; Connolly and Dalgleish 1989 for a similar classification in adults and infants').
(4) Object projection: all palmar and digital grips performed with one hand were classified based on the orientation of the spoon in the hand: projected from the radial side of the hand (i.e., radial grip), projected from the ulnar side of the hand (i.e., ulnar grip), or perpendicular to the palm (i.e., ventral grip). See also Connolly and Elliott (1972) and McCarty et al. (2001) for a similar classification.

Using these parameters, grasps produced by infants in our sample fell within the following eight grip types: palmar radial, palmar ulnar, palmar ventral, digital radial, digital ulnar, digital ventral, head-end and bimanual grasps. For a full depiction of grip types, see Fig. 3. Description of these four parameters is essential as each grip type produced by infants in our sample could be derived from them, i.e., any variation in one or more than one of these parameters would have led to a different grip type (for similar analyses and descriptions grasp classifications in typically developing infants see also Connolly and Dalgleish 1989 and McCarty et al. 2001). Following Connolly and Dalgleish (1989) and based on object orientation and on the grasp parameters, we grouped our eight grip types into two larger categories:

(a) grasp types facilitating functional spoon use (i.e., palmar radial, palmar ventral, digital radial, digital ventral);
(b) grasp types hindering functional spoon use (i.e., palmar ulnar, digital ulnar, head-end and bimanual).

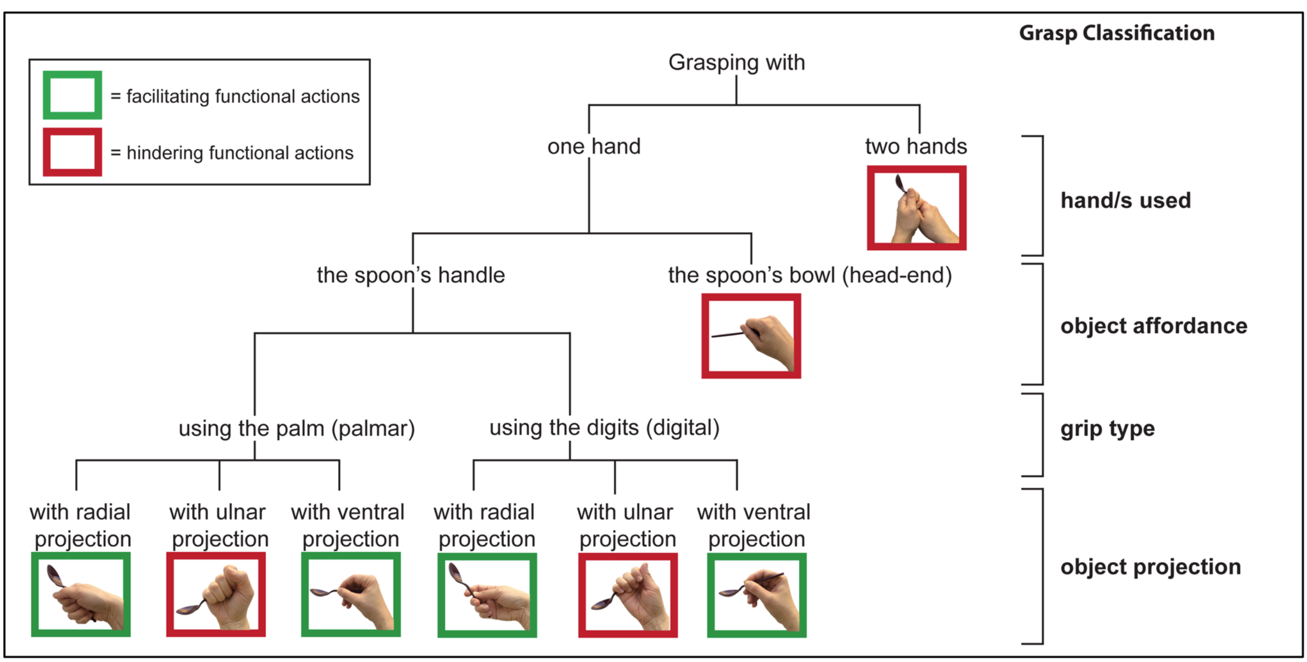

Fig. 3 Grasp types and their classification

See Fig. 3 for a description of this classification.

Functional Actions

Presence of a functional action with the spoon was coded if during the duration of the task the infant produced one or more of the following actions: dipping the spoon in the bowl as if gathering food, stirring spoon in bowl as if mixing, bringing the spoon to the mouth as if eating (see also Fenson et al. 1976; Zelazo and Kearsley 1980 for similar definitions).

Reliability

All videos were coded by a coder blind to infants' group membership. Reliability was assessed by having a second coder, also blind to group membership, code 19.5% of sample participants. Videos for 8 infants were randomly selected for double coding and utilized for reliability calculations. All ages and all outcome groups were represented in the second coder sample (30 videos, as 2 videos were missing from the randomly selected second coder sample). Following this procedure, inter-coder agreement was 96.6% for infant posture (we were unable to calculate kappa for this variable due to only one instance of "standing" being coded by one coder), 86.7% (kappa = .825) for spoon placement, and 80.0% (kappa = .204; 6 disagreements total) for spoon presentation (i.e. dynamic or static). Reliability was 100% (kappa = 1) for identifying grasp production and 100% (kappa = 1) for identifying functional actions. As for grasps, inter-coder reliability was 100% (kappa = 1) for hands used (i.e., one hand or bimanual), 88.8% (kappa = .727) for grip type (i.e., palmar or digital), and 92.6% (kappa = .868) for object orientation (i.e., radial, ulnar, ventral or head-end).

Data Analysis

We investigated: (1) group differences in the numbers of infants producing grasps and differences in the production of specific grasp types using the Fisher's exact test for 2 × 2 contingency tables and the Freeman–Halton extension of the Fisher's exact test for larger contingency tables; (2) group differences in the numbers of infants producing functional actions using the Fisher's exact test for 2 × 2 contingency tables and the Freeman–Halton extension of the Fisher's exact test for larger contingency tables; (3) linear regression analyses were used in order to analyze the relationship between functional action production and later language, controlling for 12 month cognitive scores. In analyzing functional action production we only included children who grasped the spoon. The Fisher's exact test is considered a more accurate analytic technique for contingency tables when sample sizes are relatively small.

Results

Preliminary Analyses

The ESCS spoon and bowl task lasted a little over 12 s on average (M = 12.43; SD = 8.81). No differences were found between outcome groups at any time point in *task duration*. In relation to *infant posture*, participants were mostly sitting at the table (i.e. 82.11% of the trials), and there were no differences between outcome groups in the percentage of trials during which infants were sitting vs. standing. As for *spoon presentations*, the vast majority were static presentations (87%). Furthermore, there were no differences between outcome groups in the percentage of infants for whom the spoon was moving vs. static when the child was reaching for it. In relation to *spoon placement*, the most common one was Placement 3 (51.8% of trials) (see Fig. 2), with no differences in the proportion of children receiving each of the spoon placements, whether we took the eight different presentations separately or we collapsed the frequent and rare ones as shown in Fig. 2.

Grasp Production

In relation to *grasp production* there were no differences at any age point in the numbers of infants who grasped the spoon and by 10 months of age 75.6% of infants in our sample produced at least one spoon grasp within the spoon and bowl task (see Table 3).

Considering all groups, regardless of diagnostic outcome, percentage of infants producing *grasp types* facilitating functional use progressively increased with age after 12 months (see total values Table 4 part A). Examining all infants together, the highest increase was noticeable between 12 and 18 months (+ 17.4%). However, closer observation of individual groups based on clinical outcome showed that, while both HR-LD and HR-ND groups showed a progressive increase in *grasp types* facilitating functional use, in the HR-ASD group *grasp types* facilitating functional use only increased between 12 and 18 months, while they decreased between 18 and 24 months (see group values in Table 4 part A).

A nearly significant difference between groups emerged at 24 months in percentage of infants producing grasps with facilitating vs. hindering grasp types (p = .052). Specifically, while nearly all HR-ND (14/15) and HR-LD (9/10) infants produced facilitating grasps at this age point, only about half of HR-ASD infants did so (5/9). The number of HR-ASD infants producing facilitating grasps was significantly lower than the number of HR-ND infants producing facilitating grasps ($p = .047$). The percentage of

Table 3 Number of infants in each outcome group grasping the spoon at each age point

Month	Diagnosis	Total N	No trial[a]	No grasp[b]	Grasp[c]
10	HR-ND	15	1	2	12
	HR-LD	15	0	5	10
	HR-ASD	11	1	1	9
12	HR-ND	15	0	1	14
	HR-LD	15	0	0	15
	HR-ASD	11	2	1	8
18	HR-ND	15	0	2	13
	HR-LD	15	0	0	15
	HR-ASD	11	0	0	11
24	HR-ND	15	0	0	15
	HR-LD	15	3	2	10
	HR-ASD	11	2	0	9

[a]Number of missing trials due to infants missing a visit, lack of ESCS or spoon and bowl task administration or very poor video quality precluding coding

[b]Number of children that did not grasp the spoon during the spoon and bowl task

[c]Number of children that grasped the spoon during the spoon and bowl task

HR-LD infants producing facilitating grasps did not differ significantly from either the HR-ND ($p = 1.0$) or HR-ASD groups ($p = .141$).

Functional Action Production

For functional actions, considering all outcome groups, the percentage of infants producing a functional action increased over time (see total values in Table 4 part B). Closer analysis of individual outcome groups' behavior showed that all three groups displayed this pattern, but on different time scales. While more than half of the HR-ND group produced functional actions from as early as 10 months, the HR-LD and HR-ASD groups started with fewer infants producing functional actions and increased more sharply over time (see group values in Table 4 part B). In particular, group differences in the numbers of infants producing functional actions were apparent at 10 months ($p = .013$): while infants in the HR-ND and HR-LD started to produce functional actions at 10 months, none of the HR-ASD infants produced functional actions at this age. This difference was significant between the HR-ASD and HR-ND groups ($p = .007$), but not between the HR-ASD and the HR-LD groups ($p = .211$) nor between the HR-ND and HR-LD groups ($p = .231$).

Relation Between Functional Action Production and Language Development

We investigated whether functional action production at 10 months predicted the CDI-WG words understood and words produced at 12 months and the CDI-WS words produced at 24 and 36 months. We ran four linear regressions predicting 12 month words comprehended, 12 month words produced, and 24 month words produced with functional action production at 10 months. In all analyses, we also controlled for 12 month non-verbal cognitive ability by including 12 month visual reception scores from the Mullen. Table 5 displays the full regression results for these analyses. As can be seen in the table, production of functional actions at 10 months was significantly predictive of 12 month words comprehended, $\beta = .43$, $t(27) = 2.45$, $p = .021$, 24 month words produced, $\beta = .62$, $t(25) = 3.97$, $p = .001$, and 36 month words produced, $\beta = .38$, $t(26) = 2.05$, $p = .050$, when controlling for 12 month visual reception scores. Production of functional actions at 10 months was not related to 12 month words produced scores.

Table 4 Percent of infants producing facilitating grasp and functional action at each age point

	Outcome group	Month							
		n[a]	10	n	12	n	18	n	24
A									
% Producing facilitating grasp	Total	31	61.3%	37	59.5%	39	76.9%	34	82.4%
	HR-ND	12	58.3%	14	64.3%	13	76.9%	15	93.3%
	HR-LD	10	50.0%	15	60.0%	15	80.0%	10	90.0%
	HR-ASD	9	77.8%	8	50.0%	11	72.7%	9	55.6%
B									
% Producing functional action	Total	31	32.3%	37	40.5%	39	66.7%	34	79.4%
	HR-ND	12	58.3%	14	50.0%	13	61.5%	15	73.3%
	HR-LD	10	30.0%	15	40.0%	15	80.0%	10	80.0%
	HR-ASD	9	.0%	8	25.0%	11	54.5%	9	88.9%

[a]Number of infants for which a trial was present in which they grasped the spoon for each group at each time point

Table 5 Regression results for the relation between functional action production at 10 months and CDI scores at 12, 24 and 36 months

Independent variables	DV: 12 month words understood			DV: 12 month words produced			DV: 24 month words produced			DV: 36 month words produced		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
10 month functional action production	18.14*	7.42	.43	.69	5.19	.02	32.72**	8.24	.62	13.83*	6.74	.38
Mullen visual reception 12 months	− .16	.38	− .07	.64*	.27	.42	− .03	.42	− .01	.02	.34	.01
Constant	23.82	20.07		5.80	14.04		15.94	21.96		3.28	18.24	
R^2	.19			.17			.39			.14		

*$p < .05$, **$p < .01$

Discussion

In this study we coded videos of 41 HR infants' at 10, 12, 18 and 24 months of age during a semi-structured assessment involving spontaneous spoon use in a standardized play-like task. Existent data on spoon grasping during feeding in typical populations shows that around 9–10 months infants start performing some spoon grasping and previous research showed that delays in overall grasping production attenuate by 10 months in HR infants (Libertus et al. 2014; Kaur et al. 2015; Gesell and Ilg 1937; Gesell et al. 1934). Extending previous research, we found that by 10 months more than half of HR infants in our sample (75.6%) grasped the spoon, and no differences between outcome groups were found in percentages of HR infants grasping the spoon.

Results also showed that percentages of HR infants producing grasp types facilitating functional spoon use seemed to progressively increase after 12 months when considering all groups, regardless of diagnostic outcome. However, observation of individual outcome groups showed that this progressive increase was present only in the HR-ND and the HR-LD groups, while the HR-ASD group displayed a more irregular trajectory (i.e., percentages of grasp types facilitating functional spoon use were lower in this group and increased between 12 and 18 months, but decreased between 18 and 24 months). This result highlights the importance of considering diagnostic outcome groups within HR populations and suggests that looking at grasp frequency may be a good strategy to detect differences among HR infants at younger ages (e.g. 6 months) regardless of diagnostic outcome (Libertus et al. 2014), while analyzing *qualitative* measures (e.g. grasp types) may be a more appropriate strategy after 10 months of age in relation to diagnostic outcome.

Interestingly, analyses of grasp production in relation to diagnostic outcome also showed that by 24 months of age the number of children producing a facilitating vs. hindering grasp in the HR-ASD group was only slightly above chance, while almost all children in both the HR-ND and the HR-LD groups produced facilitating grasps, even if significant differences were found only between the HR-ASD and HR-ND groups. This result extends previous findings on overall purposeful actions in HR-ASD infants (LeBarton and Iverson 2013; Landa and Garrett-Mayer 2006), by highlighting specific differences in *how* HR-ASD infants grasp a spoon to use it.

Our data on HR-ND and HR-LD is in line with previous research on frequency of grasp types in typically developing children, showing that grasps facilitating spoon use gradually increase between 11 and 24 months of age, with the highest increment in radial grips (i.e., facilitating grasps) occurring between 12 and 18 months (Connolly and Dalgleish 1989). Similarly to what has been observed in typical development, HR-ND and HR-LD infants tended to progressively abandon grasps hindering spoon use (see Fig. 3), even if they initially may allow young infants to hold the spoon in a very stable configuration. On the other hand, grasps with radial or ventral projection, facilitating spoon use and comparatively more complex and less stable (see Fig. 3), gradually grew. Therefore, our taxonomy for grasp classification proved effective in capturing changes in grasp types in HR infants.

The difference observed in performance of the HR-ASD group at 24 months may have been the result of prior delays in fine-motor skills and perception routines, which precede and support the emergence of diverse grasp types (Lockman 2000). For example, documented lower frequencies of grasping at 6 months (Libertus et al. 2014), general tendencies to explore objects by looking at them rather through manipulating them at 6 and 15 months (Kaur et al. 2015), and reduced bimanual coordination and mouthing during object play between 6 and 9 months (Bhat et al. 2009; Koterba et al. 2014), may all contribute to this effect. Ozonoff et al. (2008) also report that HR infants later diagnosed with ASD display unusual object exploration at 12 months of age compared to HR infants receiving other diagnoses (i.e., language delay, developmental delay, hyperactivity, anxiety) or no diagnosis (Ozonoff et al. 2008). Given the importance of grasping and visuo-motor exploration of objects for infants' learning of object affordances and acquisition of manipulation skills, reduced early manipulation in HR-ASD infants may have led to reduced consolidation of facilitating grasp types, as observed in the present study.

Further explanation may lie in overall difficulties with motor planning documented in HR-ASD infants. In fact, the ability to produce facilitating grasps relies among other things on appropriate planning of the reaching phase (in relation to target size and affordances) and of action phases (which both follow the grasp and are anticipated by it) (von Hofsten and Rönnqvist 1988; Rosenbaum et al. 2012). A recent longitudinal study by Focaroli et al. (2016) analyzed the reaching kinematics in a group of HR infants at 18, 24 and 36 months. They found less efficient planning of the reaching phase (measured as lower values in mean acceleration) in HR infants with respect to low risk controls, when infants had to reach for a target whose shape required discrimination among grasp types (i.e., a cube) and use it in actions requiring precise motor planning and control (i.e., stacking blocks). To the contrary, no differences emerged when infants were required to reach for a target allowing easier or indiscriminate grasp types (i.e., a sphere) and use within simpler actions (i.e., throwing the sphere in a tube). Furthermore, Cattaneo et al. (2007) also highlighted specific difficulties in both planning and understanding action sequences in terms of goals (i.e., grasping an object to bring it to the mouth or to place it in a container) in older children with ASD compared to typically developing peers (Cattaneo et al. 2007). Difficulties in interpreting the goal of others' actions based on differences in grasp types (e.g., grasping a mug from its handle to drink vs. grasping a mug from the brim to put it away), have been described in older children with ASD (Boria et al. 2009; Sparaci et al. 2014).

Given that this is the first study targeting development of grasp types in HR infants, further research is needed to fully understand mechanisms underlying observed differences in the HR-ASD group. Interestingly a recent study by Libertus and Landa (2014) has shown that HR infants respond positively to parent-implemented training targeting reaching and grasping at 3 months of age. Our hope is that the present data may extend this finding by suggesting further ways to analyze grasp types in HR infants and trigger further studies on early intervention strategies targeting grasp types and tool use. Grasp parameters, described in this study, may also find further use in future analyses of grasp types in HR populations. For example, dedicated studies may consider analyzing data from repeated grasp production in HR infants, in order to provide a more detailed description of the evolution of grasp types in HR populations, similar to the one available for typically developing children (see Connolly and Dalgleish 1989 for a sample study analyzing repeated grasping in typical development).

We also found that percentages of HR infants producing functional actions increased at each time point, with the greatest increase again appearing between 12 and 18 months of age. This finding is in line with data from previous studies on typical development showing that functional use of tools within play scenarios (e.g., stirring a spoon in a cup) increases between 11 and 20 months of age (Fenson et al. 1976; Zelazo and Kearsley 1980). Therefore, in relation to functional action production, HR infants as a group display similar developmental patterns to the ones observed in typical development.

However, percentages of infants producing functional actions by 10 months were lower in the HR-LD and HR-ASD groups. This result is in line with previous studies showing that HR-ASD infants show initial delays in functional play that decrease with age (Christensen et al. 2010; Campbell et al. 2016). However, contrary to our predictions, significant differences in functional acts were detected earlier than 18 months. Possibly this was due to specific focus on functional actions rather than overall levels of functional play in scenarios containing diverse toy sets. Extending previous findings, the present data indicate that functional actions emerge later in HR-ASD infants and that percentage of HR-ASD infants producing functional actions increased only after 18 months.

To our knowledge this is the first study specifically targeting functional actions with a spoon in HR infants, considering multiple time-points and distinguishing among outcome groups. Overall difficulties in grasping and motor planning mentioned above may have also affected the production of functional actions in HR-ASD infants. In fact, even if grasp type production per se does not directly influence functional action production (i.e., infants start producing functional actions while still using grasps that may result in uncomfortable tool use), grasp types that reduce object exploration at younger ages may lead to difficulties with object shape perception and categorization (Smith 2003; James et al. 2014). In other words, functional actions may appear later in HR-ASD infants because they have yet to establish the necessary link between object shape, object manipulation and object function due to documented reduced grasp frequency earlier in development and later unusual object exploration. Another viable interpretation is that ASD children's reduced observational learning offers them fewer opportunities in infancy to learn from others' use of tools (Williams et al. 2005). Lack of a propensity to observe and imitate others in everyday object use during infancy (e.g., spoon use during feeding), and to find participation in social learning experiences rewarding and salient, has often been stressed in ASD (Vivanti 2015; Vivanti and Rogers 2014; Williams et al. 2005).

Another interesting aspect is the behavior of our HR-LD infants, as their performance in relation to both grasp types at 24 months and functional actions at 10 months was indistinguishable from the performance of other outcome groups. Various studies have shown that language delays are not only frequent in HR infants compared to low risk controls, but still persist at 54 months of age, whereas cognitive delays may disappear (Yirmiya et al. 2006a, b; Gamliel et al. 2007). Notwithstanding evidence of persistent language impairments in HR infants, very few studies provide data on clinical outcome groups or include a HR-LD group. One of the few longitudinal studies on HR infants between 6 and 24 months considering three HR outcome groups (i.e., ND, ASD or LD) has shown that while differences between HR-ASD and HR-ND infants appear by 14 months, HR-ASD and HR-LD infants only begin to differ by 24 months (Landa and Garrett-Mayer 2006). This may explain lack of significant differences between the HR-ASD and the HR-LD at younger ages in our study. In this study the HR-LD group's behaviors seemed to be somewhere in the middle of the HR-ND and the HR-ASD groups. These results depict a more nuanced image of HR infants, but it also points out the importance of parsing out HR-LD outcome groups in studies on HR infants to better understand early emerging features of the broader autism phenotype (Stone et al. 2007).

Given that functional actions have been observed to have far-reaching consequences for infants' development of communication in typical development, we also evaluated whether production of functional actions at 10 months related to vocabulary acquisition in our HR population as measured by the same standardized measures (i.e., CDIs) used in previous studies (Bavin et al. 2008). In line with our predictions based on data from previous studies on typical development, actions with objects at 10 months significantly predicted word comprehension at 12 months. Differently from previous studies they also predicted words produced at 24 months, but not at 12 months. Furthermore, functional actions also predicted words produced at 36 months. Data indicate that for younger ages words comprehended may be a more appropriate measure, while at older ages words produced are also affected. This is understandable given that word comprehension often precedes word production, so effects on production may only be captured later in development as children produce more words. These results also seem to support the theory that difficulties in relating to objects may have significant cascading effects in communication and social interaction in HR infants at later ages (Iverson 2010; Bhat et al. 2011). In particular, the observed relation to vocabulary acquisition could be due to the fact that scarce production of functional actions with tools reduces the occurrence of social interactions supporting object naming (Iverson 2010). Observed differences in functional acts may also have an effect on visuo-perceptual object knowledge, which has been shown to support word learning in typical development (Smith 2003; James et al. 2014).

Taken together, results on production of grasp types, functional actions and vocabulary in HR infants support previous evidence of delays in purposeful actions in infants who go on to have ASD, as well as a relation between functional action production and communication (see Bhat et al. 2011 for a review). Nonetheless some limitations to the present study must be considered. These include presence of only one repetition of the task per infant at each time point and considering only one tool, as well as lack of an LR control group. Future studies should consider multiple repetitions and tools. Use of multiple tools may allow us to determine when HR infants begin to discriminate grasp types in relation to different objects, since similar protocols have led to interesting results in typical development (McCarty et al. 1999). Considering multiple repetitions may also allow us to measure differences in use of palmar vs. digital grips in HR infants. Furthermore, future research may extend current findings by providing comparisons between HR and LR infant populations. The present work has attempted to overcome this limitation by including outcome measures at 36 months and an HR-ND group. Finally, further studies may also consider parsing out the relation between functional actions and cognitive functioning by considering other control groups (e.g., infants with Down syndrome). Hopefully, the taxonomy for grasp classification provided in the present study may be extended to further studies and foster further research on grasp types in HR infants. Current results also suggest that developmental differences in some skills may be useful if detected in HR-ASD groups before the emergence of language. In particular, the difference in functional action production is particularly striking and may require further studies to fully evaluate its implication for early identification of communication difficulties in ASD, and to better understand HR-infants' progress from using tools to using language.

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Author Contributions Dr. LS was responsible for overall study design, building the coding grids and coding videos and preparing the manuscript. Ms. JBN carried out all data mining and statistical analyses. Dr. OC and Dr. JMI acted as Senior supervisors throughout the study. All co-authors read, edited, and approved the manuscript.

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Compliance with Ethical Standards

Conflict of interest The authors have no conflict of interest.

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