

## Infants Born Preterm Demonstrate Impaired Object Exploration Behaviors Throughout Infancy and Toddlerhood

Michele A. Lobo, Elena Kokkoni, Andrea Baraldi Cunha, James Cole Galloway

**Background.** Object exploration behaviors form the foundation for future global development, but little is known about how these behaviors are exhibited by infants born preterm.

**Objective.** The study objective was to longitudinally compare a comprehensive set of object exploration behaviors in infants born preterm and infants born full-term from infancy into toddlerhood.

**Design.** Twenty-two infants born full-term and 28 infants born preterm were monitored as they interacted with objects throughout their first 2 years.

**Methods.** Infants were provided up to 30 seconds to interact with each of 7 objects across 9 visits. Experimenters coded videos of infants' behaviors. Growth modeling and *t* tests were used to compare how much infants exhibited behaviors and how well they matched their behaviors to the properties of objects.

**Results.** Infants born preterm explored objects less in the first 6 months, exhibited less visual-haptic multimodal exploration, displayed reduced variability of exploratory behavior in a manner that reflected severity of risk, and were less able to match their behaviors to the properties of objects in a manner that reflected severity of risk. Infants born preterm with significant brain injury also had impaired bimanual abilities.

**Limitations.** There was a limited sample of infants born preterm with significant brain injury.

**Conclusions.** Infants born preterm have impaired abilities to interact with objects even in the first months of life. This impairment likely limits the knowledge they acquire about objects and about how they can act on them; this limited knowledge may, in turn, impair their early learning abilities. These results highlight the need for assessment and intervention tools specific for object exploration in young infants.

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Object exploration behaviors form the foundation for future development across domains. For instance, active experience with objects informs infants about the properties of objects and facilitates their learning of object discrimination, categorization, tool use, and language.<sup>1-4</sup> The ability to act on objects likely plays a key role in early development because it is a strong determinant of the amount and type of information that is available for infants to perceive, process, and use for learning.

For infants with typical development, there is a strong drive to interact with objects, even early in life.<sup>5,6</sup> Infants begin to use their existing abilities to explore objects within the first days of life.<sup>6,7</sup> By 6 months, infants have already become sophisticated in exploring objects with high intensity, variability, and combinations of behaviors.<sup>8</sup> After 6 months, infants continue to explore objects using a range of behaviors, such as fingering, picking, and looking, and these behaviors are exhibited differently in relation to the properties of objects.<sup>9-11</sup>

Despite the fact that object exploration behaviors are considered important precursors for global development, surprisingly few studies have been done to assess these behaviors in populations at risk for future developmental delays, such as infants born preterm.<sup>12</sup> Infants born preterm have heightened risks for future impairments in motor skills, working memory, problem solving, language, and learning that negatively affect their academic performance at school age.<sup>13-16</sup> These risks are even greater for infants born preterm with significant brain injury (PTBI).<sup>15,17</sup> Our recent research suggests that learning and cognitive impairments are present in infants born preterm as early as the first months of life.<sup>14</sup> Therefore, one might anticipate that the way in which these infants interact with objects and the amount and type of information that they gather about objects might differ from infants with typical development.

The aim of this project was to assess object exploration behaviors in infants born full-term (FT) and infants born preterm. We hypothesized that infants born preterm would demonstrate impaired object exploration for several reasons. First, these infants have been shown to have early impairments in postural control, visual attention, and limb coordination, all foundational skills for object exploration.<sup>18-22</sup> Second, infants born preterm have impaired early reaching abilities.<sup>23,24</sup> The ability to reach has been shown to increase the amounts of interaction and exploration that infants perform with objects during daily play.<sup>25</sup> Finally, because these impairments are generally more severe for infants born preterm with other risk factors, such as brain injury, we hypothesized that object exploration behaviors would be more impaired for infants born preterm with brain injury.<sup>26,27</sup>

A few studies have suggested that early object play is different for infants born preterm, especially those born with other risk factors, such as brain injury. For instance, at 6 months of age, infants born preterm with high risk shifted their looks less often, noticed fewer objects, and demonstrated less examination of objects during play with their mothers.<sup>22</sup> At 8 months, infants born preterm explored familiar objects longer and demonstrated less preference for novel objects than did infants born FT.<sup>28</sup> At 9 months, infants born preterm with high risk used less fingering, rotating, and transferring behaviors with objects than did infants born FT and infants born preterm with low risk.<sup>27</sup> Even infants born late preterm demonstrated less mouthing and delayed cyclical arm movement from 5 to 7 months of age.<sup>29</sup> These altered play interactions with objects likely affect the ways in which caregivers engage infants with toys. For instance, mothers of infants born preterm with high risk needed to provide more assistance and guidance to elicit object exploration behaviors from their 12-month-old infants than did mothers of infants without such risk.<sup>30</sup> The amount and quality of object exploration by infants born preterm can even predict future cognitive abilities.<sup>22,27,31</sup> Therefore, object exploration behaviors play a significant role in shaping early learning and future cognition and may develop differently in infants born preterm.<sup>27,32</sup>

These studies on early object exploration in infants born preterm have provided important insights about the experiences that affect learning and development in this at-risk population. However, significant gaps remain in basic knowledge. Studies typically have been done to assess object exploration later in development, at limited time points, and with a restricted set of mea-



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- **eTable 1:** Model-Estimated Intercepts and Standard Deviations for Infants Born at Various Terms
- **eTable 2:** Raw Data Means and Standard Errors of the Mean for Each Behavior Over Time for Infants Born at Various Terms
- **eTable 3:** Analyses of Whether Infants Born at Various Terms Exhibited Behaviors Differently With Objects Expected to Elicit Different Levels of Behavior

tures.<sup>5,6,22,27</sup> These parameters have limited the abilities to understand the early learning process, to identify important developmental patterns, and to assess the role of variability in early object exploration.<sup>33</sup>

The purpose of this study was to fill these gaps by assessing object exploration behaviors longitudinally and comprehensively in infants born preterm. We monitored infants born FT and infants born preterm as they interacted with the same objects throughout their first 2 years. We examined important variables, including bilateral holding, multi-modal behaviors, and variability (or diversity) of behaviors.<sup>34</sup> We compared how much infants exhibited behaviors and how well infants adapted their use of those behaviors to act on objects with different properties.<sup>35</sup> We hypothesized that, compared with infants born FT, infants at risk would perform a smaller amount of exploration, would perform less variable exploration (less diversity of behaviors), and would not similarly adapt their behaviors relative to the properties of objects. We expected these differences to be greatest in infants born PTBI.

## Method

### Participants

Parents of 50 infants consented to participate over a 2.5-year period. Twenty-two infants were born FT without medical complications or diagnoses. They were recruited from the community. Twenty-eight infants were born preterm between 22 and 30 weeks of gestation. They were recruited from a regional level 3 neonatal intensive care unit. Twenty-two of these infants did not have periventricular leukomalacia or grade III or IV intraventricular hemorrhage and were identified as born preterm without significant brain injury (PT no BI). The remaining 6 had periventricular leukomalacia, grade III or IV intraventricular hemorrhage,

or both and were identified as PTBI. Table 1 shows more details about the participants.

### Procedure

All participants were seen in their homes at 0, 1.5, 3, 4, 6, 9, 12, 18, and 24 months of corrected age. Participants were provided opportunities to interact with the same 7 objects in a random presentation order (Fig. 1). Objects varied in size, shape, texture, hardness, color, and existence of moving parts. Before participants were reaching, objects were placed in their hand by the experimenter, who alternated the hand of placement with each new object. After reaching onset, objects were presented within reach at midline. If a participant did not grasp an object, then the experimenter placed it in the participant's hand.

Participants were video recorded with frontal and side view camcorders as they interacted with each object for up to 30 seconds. If a participant dropped an object, then the

experimenter immediately replaced it in the participant's grasp. If the participant dropped the object more than 3 times before 30 seconds, then that trial terminated and the next began. Participants were in the supine position on a blanket on the floor through 6 months and in a seat after that because these postures are typical for these ages. The young infants in this study maintained the supine position without rolling for the duration of the assessment through 6 months.

The object exploration assessment was part of a larger study tracking early learning and development in infants with high risk. One experimenter conducted visits, at times with the help of an assistant. Visits typically lasted between 30 and 90 minutes, increasing in duration with age.

### Behavioral Coding and Outcome Variables

A total of 6 experimenters unaware of the study hypotheses and infants'

## The Bottom Line

### What do we already know about this topic?

Object exploration facilitates global development in infants.

### What new information does this study offer?

This study is the first early, longitudinal, comprehensive assessment of object exploration behaviors in infants born preterm. Infants born preterm explored objects less than did infants born full-term in terms of amount of behavior, behaviors combining senses, and variability. Infants born preterm were more likely to act similarly with objects, even though different behaviors might be more appropriate for different objects, such as shaking a rattle or feeling a furry toy.

### If you're a patient or a caregiver, what might these findings mean for you?

Results suggest early intervention providers should focus as early as possible on advancing amount and variability of object exploration experiences for infants born preterm.

## Impaired Object Exploration Behaviors in Infants Born Preterm

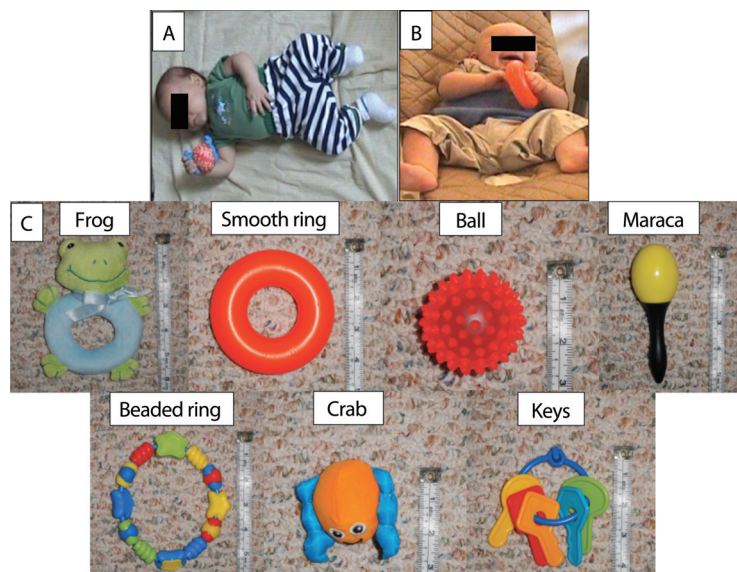
**Table 1.**

Demographic Information About Participants<sup>a</sup>

Factor	FT Group	PT no BI Group	PTBI Group
Male	12 (55)	6 (27)	2 (33)
Female	10 (45)	16 (73)	4 (66)
Caucasian	16 (73)	8 (36)	3 (50)
Black	4 (18)	11 (50)	1 (17)
Asian	2 (9)	3 (14)	2 (33)
Hispanic	0 (0)	3 (14)	1 (17)
Gestational age at birth, wk <sup>b</sup>	39.4 (0.2)	26.6 (0.4)	27.8 (0.8)
Very preterm: <32 wk	0 (0)	6 (27)	4 (67)
Extremely preterm: <28 wk	0 (0)	16 (73)	2 (33)
Birth weight, g <sup>b</sup>	3,254 (117)	881 (57)	1,084 (88)
Very low birth weight: <1,500 g	0 (0)	7 (32)	3 (50)
Extremely low birth weight: <1,000 g	0 (0)	15 (68)	3 (50)
Receiving physical therapy	0 (0)	10 (45.5)	3 (50)
Receiving occupational therapy	0 (0)	6 (27.3)	7 (31.8)
Receiving speech therapy	1 (4.5)	7 (31.8)	1 (16.7)

<sup>a</sup> Values are reported as numbers (percentages), unless otherwise indicated. FT=born full-term, PT no BI=preterm without significant brain injury, PTBI=preterm with significant brain injury.

<sup>b</sup> Values are reported as means (standard deviations).



**Figure 1.**

Assessment of infants' behaviors in the supine position through 6 months (A) and in the sitting position after 6 months (B) as they explored the same 7 objects (C) on repeated occasions through 2 years of age. The objects varied along a range of characteristics, including size, shape, texture, and sound-making ability.

medical and birth histories coded the participants' behaviors with objects by using MacSHAPA coding software\* for a time period of 1.5 years. Coders were trained until they met an interrater reliability of greater than 85% with the primary coder, on the basis of the equation  $[\text{agreed}/(\text{agreed} + \text{disagreed})] \times 100$ . Twenty percent of the data were recoded for reliability. After each experimenter coded 5 visits for data analysis, he or she recoded one of his or her own visits and one of the primary coder's visits for reliability. Average interrater reliability was 87.0% (SD=1.5%). Average intrarater reliability was 88.7% (SD=3.3%).

Coders reviewed videos multiple times at one-quarter to one-half speed as needed to determine accurate start and end times for behaviors and coded different behaviors in each pass of the video. We attempted to comprehensively code all behaviors of participants that could provide opportunities for participants to gather information about objects. In the first pass, experimenters coded the following 4 behaviors: *holding* the object with the left or right hand when the infant contacted or held the object with only the left or right hand; *bilateral holding* when the infant contacted or held the object with both hands; *object transfers* at the video frame when the object left 1 hand and entered the other (frequency only); and *throws* at the frame when the object left the infant's hand in a manner that was seemingly purposeful, on the basis of observed coordinated arm movements or repetition of the behavior while appearing to enjoy it (frequency only).

In the remaining passes, experimenters coded behaviors only during the duration of holding. Trials

\* Developed by Penelope Sanderson, University of Illinois.

included only brief periods without object holding, when experimenters were retrieving dropped or thrown objects. In the second pass, experimenters coded *touching the body with the object* when the infant brought the object into contact with part of his or her body, including the head, face, trunk, arms, and legs but excluding the mouth and other hand. In the third pass, experimenters coded *fingering* when the infant moved 1 or more fingers of 1 or both hands over the surface of the object to feel it for 2 seconds or more. In the fourth pass, experimenters coded *manipulation* when the infant held the object with 2 hands and used at least 1 hand to move the parts of the object for 2 seconds or more and *picking* when the infant used his or her fingertips to make upward and downward motions to dig in and out of the object surface. In the fifth pass, experimenters coded *squeezing* when the infant applied pressure to the object with his or her fingers, on the basis of observations of the infant's fingers sinking into the surface of flexible objects or the infant's fingers flattening on the surface of inflexible objects. In the sixth pass, experimenters coded the following 3 behaviors: *cyclical arm movement* when the arm was moving continuously for more than 2 seconds with changes in direction; *banging* when the hand or object contacted a surface or the infant's body briefly during or at the end of an excursion, such as when one bangs on a drum; and *rotation* when the infant moved the object in a manner such that it rotated through at least 45 degrees. In the seventh pass, experimenters coded *mouthling* when the object was in contact with the mouth, tongue, or lips. In the final pass, experimenters coded *looking* when the infant's eyes were directed toward the object.

After experimenters coded these behaviors separately, customized programs (Filemaker Inc, Santa Clara, California) were used to review the start and end times of the behaviors to determine whether they occurred simultaneously. All behaviors were included in this process, with the exception of holding. Because behaviors were coded only during times of holding, holding always occurred simultaneously with the other behaviors. The data processing resulted in the following 8 outcome variables: *overall behavioral performance* when the infant exhibited any behavior or combination of behaviors with the object; *bouts of behavior*, or the number of times infants switched from 1 behavior with an object to another (this measure represented behavioral change rather than variability because it required only that 2 consecutive behaviors be distinct); *individual behaviors* when only 1 behavior, such as mouthing alone or looking alone, was exhibited in isolation; *combination behaviors* when 2 or more behaviors, such as looking while fingering or mouthing while picking, occurred simultaneously; *variability of individual behaviors*, or the percentage of the total possible individual behaviors of an infant; *variability of combination behaviors*, or the percentage of the observed 155 combination behaviors of an infant; *looking without acting* when the infant's eyes were directed at the object but the infant was not exhibiting any other behaviors with the object; and *looking while acting* (multimodal behaviors) when the infant's eyes were directed at the object and the infant was exhibiting another behavior with the object.

### Data Analyses

We analyzed the data with MPlus hierarchical linear modeling software (Muthén & Muthén, Los Angeles, California). To compare behav-

iors among the 3 groups (infants born FT, infants born PT no BI, and infants born PTBI) over time, we performed 2-level growth curve modeling with multiple groups. The models shown represent the best fit. When behaviors differed in their early and later rates of change, we performed piecewise growth analyses, in which we allowed for separate slopes for the early and later periods. We used *t* tests to determine whether the model-estimated intercepts differed among the groups at the start of the study and whether the rates of change (slopes) were different among the groups. For bilateral holding time, there was an abundance of zero values, so we used a zero-inflated Poisson model. This model includes 2 components or analyses, 1 based on the likelihood of having zero values and 1 that estimates intercepts and slopes expected when behaviors do occur. We used *t* tests to determine whether there were different probabilities of having zero values among the groups on the basis of the findings of this model. Degrees of freedom for all between-group comparisons were calculated by subtracting 3 from the total sample size because these analyses incorporated estimates for the 3 groups.<sup>36</sup> Significance was set at a *P* value of less than or equal to .05 with Bonferroni corrections for multiple tests. Because Bonferroni corrections are overly strict and can lead to high false-negative rates for dependent tests like those used in this study, we also reported trends that were less than or equal to 0.01. Trends are presented as preliminary results.

To determine whether participants used different behaviors to act on objects on the basis of the properties of the objects, we grouped objects on the basis of the properties expected to elicit high or low levels of the behaviors (Tab. 2). For instance, we expected more move-

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**Table 2.**

Groupings for Object Analyses

Behavior(s)	Hypothesis	Criteria for Inclusion in Group With High Level of Behavior	Objects Eliciting the Following Level of Behavior:	
			High	Low
Overall behavioral performance	Expect more for objects with smaller areas for grasping	Graspable area of <1 cm	Beaded ring, keys, maraca	Ball, crab, frog, smooth ring
Combination behaviors (duration and variability)	Expect more for objects with a variety of exploratory affordances	Two or more of the following: moving parts, textured surface, sound-making ability, patterned surface, squeezability	Ball, beaded ring, crab, frog, keys	Maraca, smooth ring
Bilateral holding	Expect more for objects with greater overall size	Overall width of >5 cm	Ball, beaded ring, crab, frog, smooth ring	Keys, maraca
Touching the body	Expect more for objects with a larger area, affording greater opportunity to contact body surfaces when held	Overall width × length of >50 cm <sup>2</sup>	Beaded ring, frog, keys, smooth ring	Ball, crab, maraca
Looking	Expect more for objects with a variety of detail and exploratory affordances	One or more of the following: surface with more than 1 color, textured surface, movable parts	Ball, beaded ring, crab, frog, keys, maraca	Smooth ring
Cyclical movement	Expect more for objects with sound-making potential	Ability to produce sound when moved	Frog, keys, maraca	Ball, beaded ring, crab, smooth ring
Fingering	Expect more for objects with textured surfaces	Textured surface (eg, soft cloth, fur, bumps)	Ball, beaded ring, crab, frog	Keys, maraca, smooth ring

ment of objects when that would result in sound production. Within each group, we performed separate 2-level growth curve modeling procedures with multiple outcomes. We used *t* tests of the model-estimated means to determine whether they were different at each visit. This approach allowed us to determine whether participants selectively exhibited behaviors more with objects expected to elicit the behaviors at each visit. Degrees of freedom for these within-group comparisons were calculated by subtracting 1 from the sample size of each of the 3 groups.<sup>36</sup> Again, a *P* value of ≤.05 with Bonferroni corrections for multiple tests was considered significant. Trends of ≤.01 are presented as preliminary results. The findings were compared with the findings for the other groups.

Effect sizes throughout are presented in terms of Pearson *r*, with

.1, .3, and .5 representing small, medium, and large effects, respectively.<sup>37</sup> Estimated growth curves were generated by hierarchical linear modeling. The variability within groups for the estimated intercepts is shown in eTable 1 (available at [ptjournal.apta.org](http://ptjournal.apta.org)). Raw data slopes for participants within each group were not variable enough for the model to estimate separate slopes for participants within each group, so the model-estimated slopes were fixed within each group, resulting in no within-group variance to report for slopes. The raw data averages and variability are shown in eTable 2 (available at [ptjournal.apta.org](http://ptjournal.apta.org)).

### Role of the Funding Source

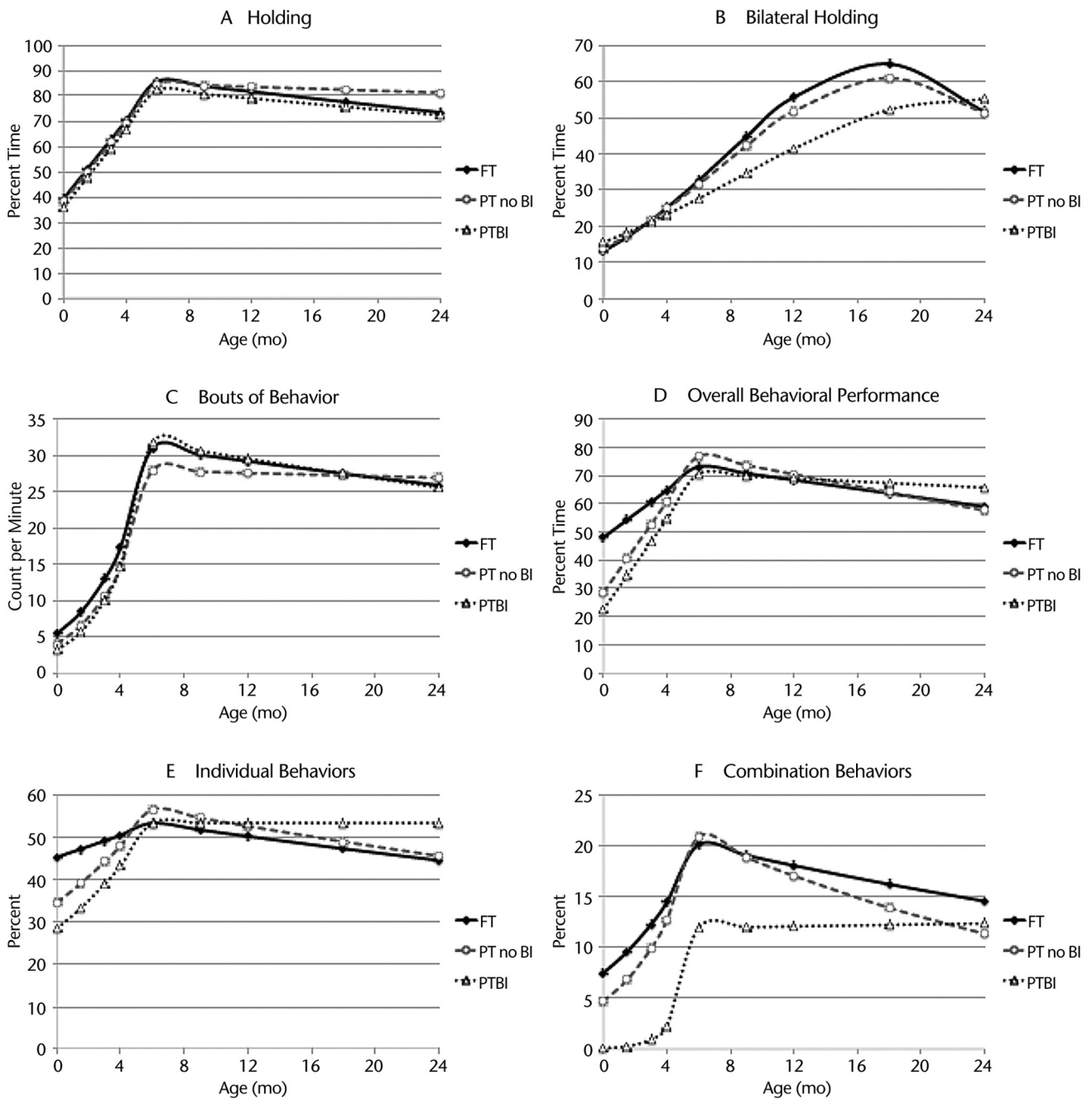
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## Results

In presenting the results, we use the terms “less” and “more” when referring to time or percentage and the terms “less often” and “more often” when referring to number of behaviors.

### Differences in Behaviors With Objects Over Time

There were no differences in the ages of the infants in the 3 groups at each visit. In addition, infants in the FT, PT no BI, and PTBI groups all held objects for similar amounts of time and exhibited similar numbers of bouts of behavior with them (Figs. 2A and 2C). When bilateral holding occurred, it occurred similarly in the 3 groups. However, there was a greater probability of zero values for bilateral holding in the PTBI group than in the other groups (Fig. 2B) (FT versus PTBI:  $t_{47}=3.81$ ,  $P=.0002$ ,  $r=.49$ ; PT no BI versus PTBI:  $t_{47}=-3.07$ ,  $P=.001$ ,  $r=.41$ ).



**Figure 2.**

(A and C) Overall holding time (A) and number of bouts of behavior (C) were similar among groups. (B) Bilateral holding time was similar among groups when it occurred, although it was significantly more common for infants born preterm with significant brain injury (PTBI) not to exhibit any bilateral holding. (D) Infants born preterm spent less time exploring objects in the first 6 months. (E) Infants born preterm also had decreased performance of individual behaviors in the first 6 months. (F) Infants born PTBI had decreased performance of combination behaviors throughout the study. FT=full-term, PT no BI=preterm without significant brain injury.

Infants in the PT no BI and PTBI groups spent less time exhibiting behaviors with the objects throughout the first 6 months than did infants in the FT group (Fig. 2D) (intercept for FT versus PT no BI:  $t_{47} = -3.73$ ,  $P = .0002$ ,  $r = .48$ ; intercept for FT versus PTBI:  $t_{47} = -3.23$ ,  $P = .001$ ,  $r = .42$ ; linear slope for FT versus PT no BI:  $t_{47} = 3.93$ ,  $P = .0002$ ,  $r = .50$ ; linear slope for FT versus PTBI:  $t_{47} = 2.39$ ,  $P = .01$ ,  $r = .33$ ). Furthermore, the behaviors that they exhibited were less variable. Infants in the PT no BI group tended to show less variability in individual behaviors and spent less time exhibiting them than did infants in the FT group throughout the first 6 months (Fig. 2E) (time intercept:  $t_{47} = -2.20$ ,  $P = .01$ ,  $r = .31$ ; linear slope:  $t_{47} = 2.36$ ,  $P = .01$ ,  $r = .33$ ; variability intercept:  $t_{47} = -2.20$ ,  $P = .01$ ,  $r = .31$ ; linear slope:  $t_{47} = 2.15$ ,  $P = .01$ ,  $r = .30$ ). Infants in the PTBI group showed less variability in their combination behaviors and spent less time exhibiting them than did infants in the other groups throughout the study (Fig. 2F) (time intercept for FT versus PTBI:  $t_{47} = -3.85$ ,  $P = .0002$ ,  $r = .49$ ; linear slope for FT versus PTBI:  $t_{47} = 3.39$ ,  $P = .0007$ ,  $r = .44$ ; linear slope for PT no BI versus PTBI:  $t_{47} = -3.40$ ,  $P = .0007$ ,  $r = .44$ ; variability intercept for FT versus PTBI:  $t_{47} = -2.20$ ,  $P = .01$ ,  $r = .31$ ; linear slope for FT versus PTBI:  $t_{47} = 2.18$ ,  $P = .01$ ,  $r = .30$ ).

There were differences in the performance of specific behaviors among the groups as well. Infants in the PTBI group exhibited many behaviors less throughout the first 2 years. Infants in the PTBI group touched their bodies with the objects less than did infants in the FT group (Fig. 3A) (intercept for FT versus PTBI:  $t_{47} = -3.68$ ,  $P = .0003$ ,  $r = .47$ ; linear slope for FT versus PTBI:  $t_{47} = 3.06$ ,  $P = .001$ ,  $r = .41$ ). There were no differences in overall looking behavior, but looking at objects

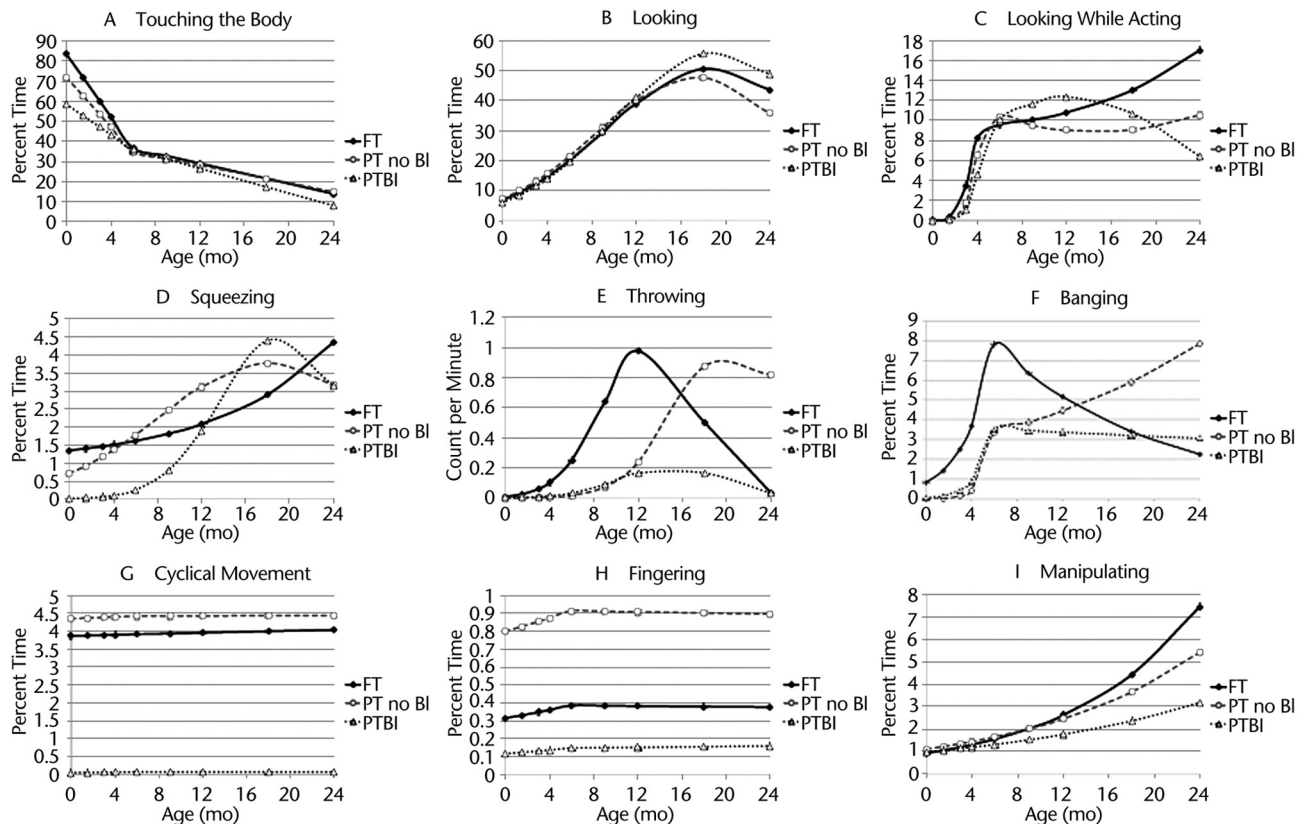
while exhibiting other behaviors with them (multimodal behaviors) occurred less in both PT groups (Figs. 3B and 3C) (intercept for FT versus PT no BI:  $t_{47} = -5.68$ ,  $P < .0001$ ,  $r = .64$ ; intercept for FT versus PTBI:  $t_{47} = -6.37$ ,  $P < .0001$ ,  $r = .68$ ; linear slope for FT versus PT no BI:  $t_{47} = 14.53$ ,  $P < .0001$ ,  $r = .90$ ; linear slope for FT versus PTBI:  $t_{47} = 15.16$ ,  $P < .0001$ ,  $r = .91$ ; quadratic slope for FT versus PT no BI:  $t_{47} = -5.64$ ,  $P < .0001$ ,  $r = .64$ ; quadratic slope for FT versus PTBI:  $t_{47} = -4.56$ ,  $P < .0001$ ,  $r = .55$ ). Infants in the PTBI group also squeezed objects less than did infants in the other groups throughout the first year (Fig. 3D) (intercept for FT versus PTBI:  $t_{47} = -6.34$ ,  $P < .0001$ ,  $r = .68$ ; intercept for PT no BI versus PTBI:  $t_{47} = 6.40$ ,  $P < .0001$ ,  $r = .68$ ; linear slope for FT versus PTBI:  $t_{47} = 23.84$ ,  $P < .0001$ ,  $r = .96$ ; linear slope for PT no BI versus PTBI:  $t_{47} = -29.95$ ,  $P < .0001$ ,  $r = .97$ ; quadratic slope for FT versus PTBI:  $t_{47} = -7.71$ ,  $P < .0001$ ,  $r = .75$ ; quadratic slope for PT no BI versus PTBI:  $t_{47} = 6.35$ ,  $P < .0001$ ,  $r = .68$ ). There were also differences in throwing behavior among the groups (Fig. 3E). Peaks were observed at 12 months for the FT group and at 18 months for the PT no BI group. Throwing happened less often and did not peak for the PTBI group (intercept for FT versus PT no BI:  $t_{47} = -5.51$ ,  $P < .0001$ ,  $r = .63$ ; intercept for PT no BI versus PTBI:  $t_{47} = -4.91$ ,  $P < .0001$ ,  $r = .58$ ; linear slope for FT versus PT no BI:  $t_{47} = 8.39$ ,  $P < .0001$ ,  $r = .77$ ; linear slope for PT no BI versus PTBI:  $t_{47} = 7.39$ ,  $P < .0001$ ,  $r = .73$ ; quadratic slope for FT versus PT no BI:  $t_{47} = -6.09$ ,  $P < .0001$ ,  $r = .66$ ; quadratic slope for PT no BI versus PTBI:  $t_{47} = -8.01$ ,  $P < .0001$ ,  $r = .76$ ). There were no differences in banging behavior, but similar trajectories were observed, with peaks at 6 months for the FT group and at 24 months for the PT no BI group and

the PTBI group showing less banging without a peak (Fig. 3F).

Trends offered preliminary suggestions that there may have been less cyclical movement and fingering of objects by infants in the PTBI group (Figs. 3G and 3H). There were trends for differences in the amount of cyclical movement by infants in the PTBI group relative to the other groups (intercept for FT versus PTBI:  $t_{47} = -2.79$ ,  $P = .004$ ,  $r = .38$ ; intercept for PT no BI versus PTBI:  $t_{47} = 2.78$ ,  $P = .004$ ,  $r = .38$ ; linear slope for FT versus PTBI:  $t_{47} = 2.71$ ,  $P = .005$ ,  $r = .37$ ; linear slope for PT no BI versus PTBI:  $t_{47} = -2.62$ ,  $P = .005$ ,  $r = .36$ ). Likewise, there were trends for differences in the amount of fingering by infants in the PTBI group relative to infants in the PT no BI group (intercept for PT no BI versus PTBI:  $t_{47} = 2.46$ ,  $P = .005$ ,  $r = .34$ ). No differences were observed for mouthing or manipulation, but manipulation trajectories suggested that the groups may have been on different trajectories (Fig. 3I).

### Differences in Behaviors With Objects in Relation to Object Properties

There were differences in terms of when the groups matched their behaviors to the properties of objects (eTab. 3, available at [ptjournal.apta.org](http://ptjournal.apta.org); Fig. 4). These results were based on within-group analyses of how participants behaved with objects expected to elicit high or low levels of each behavior (Tab. 2). For instance, infants in the FT and PT no BI groups always exhibited more behaviors with objects that were smaller and easier to grasp. Infants in the PTBI group never showed this behavioral difference. Similarly, infants in the FT group showed trends at 9 months and significant differences from 12 to 18 months for holding larger objects with 2 hands more often than holding smaller objects with 2 hands. Infants



**Figure 3.**

(A) Infants born preterm touched their bodies less with objects than did infants born full-term (FT) in the first 6 months. (B and C) Even though groups spent similar amounts of time looking at objects overall (B), infants born preterm spent less time looking at objects while exhibiting other actions on them (visual-haptic multimodal exploration) toward the latter part of the study (C). (D) Infants born preterm with significant brain injury (PTBI) squeezed objects less than did infants in the other groups throughout the first year. (E) Infants born preterm without significant brain injury (PT no BI) had a delay in their peak throwing behavior, whereas infants born PTBI exhibited throwing less often overall and did not reach a peak similar to those reached by infants born FT and infants born PT no BI. (F) There were no significant differences in banging behavior, and similar trajectories were observed for infants born PT no BI (who had a delay in their peak banging behavior) and infants born PTBI (who had lower levels of banging behavior throughout most of the study and never reached the same peak levels of performance as the other groups). (G and H) There were trends for less cyclical movement (G) and fingering (H) in infants born PTBI than in infants born FT and infants born PT no BI. (I) No differences were observed among the groups for manipulation, yet the trajectories suggested that the groups may have been headed along different paths for this behavior.

in the PT no BI group showed such trends from 12 to 18 months. Infants in the PTBI group never used more bilateral holding for larger objects. They exhibited similar amounts of bilateral holding with all objects regardless of object size.

Infants in the FT group showed trends from 3 to 4 months and significant differences from 6 to 9 months for more time exhibiting combination behaviors with objects with a variety of exploratory options and showed trends from 4 to 6

months and significance differences from 9 to 24 months for greater variability of combination behaviors exhibited with these objects. Infants in the PT no BI and PTBI groups never showed significant differences in time exhibiting combination behaviors, and infants in the PTBI group did not show differences in the variability of these behaviors.

Differences were observed in the matching of behavioral performance to object properties for some individual behaviors as well. For instance,

infants in the FT group touched their bodies with larger objects more often at every visit. Infants in the PT no BI group did this statistically more often at all visits except those from 9 to 12 months, when they showed trends. Infants in the PTBI group showed trends at 6 months.

There was a general pattern for the emergence of behavior-object matching first in the FT group, later in the PT no BI group, and even later or not at all in the PTBI group for many individual behaviors. For

## Impaired Object Exploration Behaviors in Infants Born Preterm

Behavior	Group	Age (mo)									
		0	1.5	3	4	6	9	12	18	24	
Overall behavioral performance	FT										
	PT no BI										
	BI										
	PTBI										
Combination behaviors (duration)	FT										
	PT no BI										
	BI										
	PTBI										
Combination behaviors (variability)	FT										
	PT no BI										
	BI										
	PTBI										
Bilateral holding	FT										
	PT no BI										
	BI										
	PTBI										
Touching the body	FT										
	PT no BI										
	BI										
	PTBI										
Looking	FT										
	PT no BI										
	BI										
	PTBI										
Cyclical movement	FT										
	PT no BI										
	BI										
	PTBI										
Fingering	FT										
	PT no BI										
	BI										
	PTBI										

**Figure 4.**

Infants born preterm showed differences from infants born full-term (FT) in the ability to match their behavioral performances to the properties of objects. Infants born preterm had delays in or the absence of this ability across multiple behaviors. Differences were most pronounced for infants born preterm with significant brain injury (PTBI). Cells shaded in gray represent visits during which increased behavioral performance was observed for objects with properties expected to elicit more of a behavior; dark gray cells represent significant differences ( $P \leq .006$ ), and light gray cells represent trends for differences ( $P \leq .01$ ). White cells represent visits during which infants exhibited the behavior similarly with all objects regardless of their properties. See Table 2 for details on the properties expected to elicit each behavior and eTable 3 for supporting statistical data. PT no BI=preterm without significant brain injury.

example, infants in the FT group looked significantly more at objects with varied surface colors, surface texture, and movable parts from 9 to 18 months, with trends at 24 months. Infants in the PT no BI group did this significantly more from 12 to 18 months, with trends at 24 months. Infants in the PTBI

group showed trends at 18 months. Similarly, infants in the FT group cyclically moved sound-producing objects more, with trends from 3 to 12 months. Infants in the PT no BI group showed significant differences from 9 to 18 months, with trends at 24 months. Infants in the PTBI group showed trends from 12 to 24

months. Furthermore, infants in the FT group showed trends for more fingering of objects with textured surfaces at 12 months. Infants in the PT no BI group showed trends at 18 months. Infants in the PTBI group showed trends at 24 months.

## Discussion

In the present study, we compared object exploration behaviors among infants born FT, infants born preterm with low risk, and infants born preterm with high risk (FT, PT no BI, and PTBI, respectively). The results revealed some similarities in object exploration among the groups for behaviors such as holding and number of behavior bouts. Therefore, infants in the 3 groups were similarly able to grasp and were motivated to interact with objects. The results also highlighted key differences in behaviors in infants born preterm—differences that were more marked in those born with significant brain injury. A limitation of the present study was that there were only 6 infants born preterm with significant brain injury. The 5 main findings of the present study are discussed below.

### Infants Born Preterm Exhibited Less Object Exploration Than Infants Born FT in the First 6 Months of Life

Infants in the PT no BI and PTBI groups held objects for similar amounts of time but spent less of this time exploring objects than did infants in the FT group in the first 6 months of life. The amount of time exhibiting behaviors with objects is important because it reflects the amount of information gathered by infants to learn about objects, their bodies, and their interrelationships.<sup>38</sup> The amount of object exploration in infancy was shown in previous studies to relate to learning and cognition. For instance, infants who explored objects more performed better in

habituation and novelty tasks.<sup>39-41</sup> On the other hand, infants born preterm exhibited reduced amounts of exploratory behaviors with objects in the present study and other studies, and the amount was proportional to the risk level.<sup>27,31</sup> This finding was shown even for infants born late preterm.<sup>29</sup> One consistent result of biological risk factors such as preterm birth, brain injury, and Down syndrome is decreased duration of object interaction.<sup>12</sup> The present study confirmed that in early development, infants born preterm may be able to hold objects in a manner similar to that of infants not born preterm but do significantly less to explore and learn about those objects.

### Infants Born PTBI Had Impaired Bimanual Abilities

Infants in the PTBI group were most likely to show a lack of bimanual contact with objects. The ability to interact with objects with both hands is critical for the performance of more complex exploratory behaviors, such as fingering and manipulation, to gather more detailed information about objects.<sup>42</sup> Early bimanual holding is also an important precursor for essential future activities, including feeding, dressing, and writing. Bimanual abilities have not been well studied in young populations at risk despite the fact that a lack of midline movement has been shown to relate to future impairments in motor and cognitive abilities.<sup>43</sup> One recent study showed that infants with neonatal stroke exhibited less bimanual object holding than did infants born FT.<sup>44</sup> Children with cerebral palsy also typically demonstrate impairments in their ability to interact with objects bimanually.<sup>45</sup> The findings of the present study demonstrated that bimanual object exploration also was impaired throughout the first 2 years of life in infants born PTBI. This means that these infants at

high risk may be chronically lacking opportunities to engage in more complex object exploration behaviors and to prepare for essential future activities of daily living.

### Infants Born Preterm Exhibited Less Visual-Haptic Multimodal Exploration

Infants born preterm spent less time exploring objects simultaneously with vision and touch than did infants born FT. This type of multimodal exploration is thought to be critical for early exploration and learning. Everyday experiences with objects involve information gathering and coordination among perceptual systems.<sup>5</sup> Multimodal experience with objects has been shown to improve infants' performance in a variety of perceptual and cognitive tasks, such as color discrimination tasks, visual occlusion tasks, and object completion tasks.<sup>46-48</sup> Multimodal exploration has been documented in studies with infants developing typically but has not been considered for infants born preterm.<sup>5</sup> The results of the present study revealed that infants born preterm exhibited less multimodal visual-haptic exploration with objects during the first 2 years of life. Multimodal exploration facilitates early learning, and infants born preterm did not exhibit this behavior as often as did infants born FT.

### Variability of Exploratory Behavior in Infants Born Preterm Was Reduced in a Manner That Reflected Severity of Risk

Infants in the PT no BI group showed less variability (or diversity) in the individual behaviors that they exhibited in the first 6 months of life. Moreover, infants in the PTBI group showed less variability in the combination behaviors that they exhibited throughout the study. The variability in the results can be interpreted through 2 perspectives. The first is as

an extension of the earlier discussion about multimodal exploration. Multimodal exploration has traditionally been defined as behaviors coordinating vision and touch. However, multimodal exploration also occurs when the kinesthetic and oral senses are coordinated with vision and touch.<sup>46</sup> Most combinations of behaviors in the present study involved the gathering of information with 2 or more of these senses. Therefore, the results could extend the earlier discussion to suggest that infants in the PTBI group demonstrated less variable multimodal exploration across all modalities assessed.

An alternative interpretation involves evaluating the role that behavioral variability plays in development. Variability has historically been considered noise in developmental studies, but it is becoming increasingly accepted as a normal and even essential part of typical development.<sup>42,49</sup> By exploring a range of behaviors and relationships among their bodies and objects, infants may acquire both new action possibilities and knowledge. For example, behavioral variability is required for learning important early, foundational skills, such as postural control, and this behavioral variability is diminished in infants with movement impairments.<sup>19,33</sup> Despite the fact that variability is a hallmark of typical development and is often diminished in populations at risk for developmental delays, the present study is the first to measure the variability of object exploration in infants born preterm. The diminished variability observed for infants born preterm suggested that they had a diminished repertoire of behavioral combinations from which to select when exploring objects and acquiring knowledge.

It is likely that the aforementioned differences in infants' exploratory

behaviors related to the common impairments of infants born preterm (noted earlier). For instance, infants must be able to control their posture for balance, for righting of the head and trunk, to provide a stable base for supporting limb movement, and to control gaze for exploring objects.<sup>50,51</sup> This ability is particularly needed for more complex behavioral performance involving both hands or combinations of behaviors.<sup>44,45</sup>

Furthermore, the differences may be related to intra- and interlimb coordination impairments in infants born preterm. These impairments have been observed in infants born preterm in relation to lower extremity behaviors.<sup>20,21</sup> It is likely that similar impairments exist for the upper extremities. This notion could explain why infants born preterm were able to hold objects in a manner similar to that of infants born FT but were not able to similarly act on objects while holding them in early development or to similarly exhibit comparable levels of multimodal, combination, and bimanual behaviors throughout the study.

The differences in exploratory behaviors observed in infants born preterm and infants born FT also may be attributed to differences in other intrinsic and extrinsic characteristics. For instance, for many children with cerebral palsy, those better able to adapt their behaviors for activities of daily living also tend to have better motor function.<sup>52</sup> This finding may reflect the fact that those children have higher levels of intrinsic characteristics, such as self-awareness, adaptability, motivation, problem solving, persistence, and risk taking. The differences in exploratory behaviors also may be the result of differences in extrinsic characteristics, such as caregiving in environments that offer different

quantities and qualities of interactions with people and objects.<sup>12</sup>

### Ability of Infants Born Preterm to Match Behaviors to the Properties of Objects Was Impaired in a Manner That Reflected Severity of Risk

There was a general trend in which infants born FT were the first to begin selectively exhibiting behaviors with objects on the basis of the properties of the objects. Such behaviors emerged later in the PT no BI group and even later, if at all, in the PTBI group. The ability to match behaviors to the properties of objects facilitates efficient and effective information gathering. If one is not able to match behaviors to the properties of objects, then learning abilities may be delayed, impaired, or both.<sup>53</sup>

It is likely that the impaired ability of infants born preterm to match their behaviors to object properties in the present study emerged, at least in part, from an early, dysfunctional cognition-perception-action loop.<sup>38,54</sup> This loop includes an impoverished history of information gathering characterized by reduced amount and variability of object exploration. In effect, infants may not have effectively learned about the properties of objects and the ways in which they could act on them. This diminished learning likely impaired the ability of infants born preterm to selectively match their behaviors to the properties of objects. As a consequence, infants may have continued to gather information about objects that was significantly limited relative to that gathered by their peers who were developing typically. An early appreciation of this dysfunctional exploration-learning loop is an important initial step to creating clinical assessment and intervention tools for young infants at risk and their families.

### Clinical Implications

The results of the present study highlight important points for early intervention practice and research for infants born preterm. First, early interventions that promote object exploration should begin in the first weeks of life because impairments that create a dysfunctional exploration-learning loop that can impair future ability and learning are already evident at this point. Examples of interventions that successfully promote object exploration include kangaroo care, reaching and object exploration play activities, caregiver education on handling and positioning, and activities that encourage increased general movement of the arms and trunk.<sup>24,55-58</sup>

Second, further research should be conducted to determine what types of interventions can have a positive effect on object exploration. One focus of intervention could be increasing the variability of early object exploration experiences.<sup>25,32,59</sup> Successful interventions may involve play in various postures with objects that have a variety of properties across a range of contexts. A second focus of intervention could be postures and activities that promote midline hand positioning and bimanual object exploration. For instance, play with larger objects and in side-lying and supine positions facilitates early bimanual activity.<sup>8,60</sup> A third focus of intervention could be the use of infant- and family-friendly rehabilitation tools, such as exoskeletons and enriched learning environments, designed to assist young infants in initiating and sustaining upper extremity actions required for typical object exploration, such as movements against gravity and toward the midline.<sup>61</sup> A fourth focus of intervention could be increasing infants' adaptive behaviors, motivation, and persistence so that they are more driven to move and explore.<sup>52</sup> A fifth focus of inter-

vention could be changing caregiving environments and social dynamics among infants and caregivers to foster frequent opportunities for exploratory encounters.<sup>56-58</sup>

Future studies also could expand on the results of the present study to create “normative” object exploration curves from which to identify delayed development, impaired development, or both; to study a larger sample of infants born PTBI; to determine the causes for early behavioral differences; and to study the impact of early object exploration differences on future learning and school readiness.

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## References

- Needham A. Improvements in object exploration skills may facilitate the development of object segregation in early infancy. *J Cogn Dev*. 2000;1:131-156.
- Lockman JJ. A perception-action perspective on tool use development. *Child Dev*. 2000;71:137-144.
- Iverson JM. Developing language in a developing body: the relationship between motor development and language development. *J Child Lang*. 2010;37:229-261.
- Karasik LB, Tamis-LeMonda CS, Adolph KE. Crawling and walking infants elicit different verbal responses from mothers. *Dev Sci*. 2014;17:388-395.
- Rochat P. Object manipulation and exploration in 2-month-old to 5-month-old infants. *Dev Psychol*. 1989;25:871-884.
- Molina M, Jouen F. Manual cyclical activity as an exploratory tool in neonates. *Infant Behav Dev*. 2004;27:42-53.
- Jouen F, Molina M. Exploration of the newborn's manual activity: a window onto early cognitive processes. *Infant Behav Dev*. 2005;28:227-239.
- Lobo MA, Kokkonen E, de Campos AC, Galloway JC. Not just playing around: infants' behaviors with objects reflect ability, constraints, and object properties. *Infant Behav Dev*. 2014;37:334-351.
- Ruff HA. Infants' manipulative exploration of objects: effects of age and object characteristics. *Dev Psychol*. 1984;20:9-20.
- Ruff HA. Role of manipulation in infants' responses to invariant properties of objects. *Dev Psychol*. 1982;18:682-691.
- Palmer CF. The discriminating nature of infants' exploratory actions. *Dev Psychol*. 1989;25:885-893.
- de Campos AC, Savelsbergh GJP, Rocha NACF. What do we know about the atypical development of exploratory actions during infancy? *Res Dev Disabil*. 2012;33:2228-2235.
- Jongbloed-Pereboom M, Janssen A, Steenbergen B, Nijhuis-van der Sanden MWG. Motor learning and working memory in children born preterm: a systematic review. *Neurosci Biobehav Rev*. 2012;36:1314-1330.
- Lobo MA, Galloway JC. Assessment and stability of early learning abilities in preterm and full-term infants across the first two years of life. *Res Dev Disabil*. 2013;34:1721-1730.
- Taylor HG, Klein N, Anselmo MG, et al. Learning problems in kindergarten students with extremely preterm birth. *Arch Pediatr Adolesc Med*. 2011;165:819-825.
- Adams-Chapman I, Bann CM, Vaucher YE, et al. Association between feeding difficulties and language delay in preterm infants using Bayley Scales of Infant Development-Third Edition. *J Pediatr*. 2013;163:680-685.
- Raz S, Debastos AK, Newman JB, Batton D. Extreme prematurity and neuropsychological outcome in the preschool years. *J Int Neuropsychol Soc*. 2010;16:169-179.
- Cioni G, Ferrari F, Einspieler C, et al. Comparison between observation of spontaneous movements and neurologic examination in preterm infants. *J Pediatr*. 1997;130:704-711.
- Dusing SC, Harbourne RT. Variability in postural control during infancy: implications for development, assessment, and intervention. *Phys Ther*. 2010;90:1838-1849.
- Heathcock JC, Bhat AN, Lobo MA, Galloway J. The relative kicking frequency of infants born full-term and preterm during learning and short-term and long-term memory periods of the mobile paradigm. *Phys Ther*. 2005;85:8-18.
- Fetters L, Sapir I, Chen YP, et al. Spontaneous kicking in full-term and preterm infants with and without white matter disorder. *Dev Psychobiol*. 2010;52:524-536.
- Landry SH, Chapieski ML. Visual attention during toy exploration in preterm infants: effects of medical risk and maternal interactions. *Infant Behav Dev*. 1988;11:187-204.
- Fallang B, Saugstad OD, Groggaard J, Hadders-Algra M. Kinematic quality of reaching movements in preterm infants. *Pediatr Res*. 2003;53:836-842.
- Heathcock JC, Lobo MA, Galloway JC. Movement training advances the emergence of reaching in infants born at less than 33 weeks of gestational age: a randomized clinical trial. *Phys Ther*. 2008;88:310-322.
- Lobo MA, Galloway JC. The onset of reaching significantly impacts how infants explore both objects and their bodies. *Infant Behav Dev*. 2013;36:14-24.
- Badr LK, Bookheimer S, Purdy I, Deeb M. Predictors of neurodevelopmental outcome for preterm infants with brain injury: MRI, medical and environmental factors. *Early Hum Dev*. 2009;85:279-284.
- Ruff HA, McCarton C, Kurtzberg D, Vaughan HG. Preterm infants' manipulative exploration of objects. *Child Dev*. 1984;55:1166-1173.
- Sigman M. Early development of preterm and full-term infants: exploratory behavior in 8-month-olds. *Child Dev*. 1976;47:606-612.
- Soares DD, von Hofsten C, Tudella E. Development of exploratory behavior in late preterm infants. *Infant Behav Dev*. 2012;35:912-915.
- Landry SH, Garner PW, Denson S, et al. Low birth weight (LBW) infants' exploratory behavior at 12 and 24 months: effects of intraventricular hemorrhage and mothers' attention directing behaviors. *Res Dev Disabil*. 1993;14:237-249.
- Kopp CB, Vaughn BE. Sustained attention during exploratory manipulation as a predictor of cognitive competence in preterm infants. *Child Dev*. 1982;53:174-182.
- Lobo MA, Harbourne RT, Dusing SC, McCoy SW. Grounding early intervention: physical therapy cannot just be about motor skills anymore. *Phys Ther*. 2013;93:94-103.
- Harbourne RT, Stergiou N. Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. *Phys Ther*. 2009;89:267-282.
- Soska KC, Adolph KE. Postural position constrains multimodal object exploration in infants. *Infancy*. 2014;19:138-161.
- Gibson JJ. *The Ecological Approach to Visual Perception*. Boston, MA: Houghton Mifflin; 1979:127-143.
- Bolger N, Laurenceau JP. *Intensive Longitudinal Methods: An Introduction to Diary and Experience Sampling Research*. New York, NY: Guilford Press; 2013:79.
- Cohen J. A power primer. *Psychol Bull*. 1992;112:155-159.

- 38 Gibson EJ. Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annu Rev Psychol.* 1988;39:1-41.
- 39 Baumgartner HA, Oakes LM. Investigating the relation between infants' manual activity with objects and their perception of dynamic events. *Infancy.* 2013;18:983-1006.
- 40 Schwarzer G, Freitag C, Schum N. How crawling and manual object exploration are related to the mental rotation abilities of 9-month-old infants. *Front Psychol.* 2013;4:1-8.
- 41 Libertus K, Gibson J, Hidayatallah NZ, et al. Size matters: how age and reaching experiences shape infants' preferences for different sized objects. *Infant Behav Dev.* 2013;36:189-198.
- 42 Atun-Einy O, Berger SE, Ducz J, Sher A. Strength of infants' bimanual reaching patterns is related to the onset of upright locomotion. *Infancy.* 2014;19:82-102.
- 43 Sherick I, Greenman G, Legg C. Some comments on the significance and development of midline behavior during infancy. *Child Psychiatry Hum Dev.* 1976;6:170-183.
- 44 Chen CY, Lo WD, Heathcock JC. Neonatal stroke causes poor midline motor behaviors and poor fine and gross motor skills during early infancy. *Res Dev Disabil.* 2013;34:1011-1017.
- 45 Greaves S, Imms C, Dodd K, Krumlinde-Sundholm L. Assessing bimanual performance in young children with hemiplegic cerebral palsy: a systematic review. *Dev Med Child Neurol.* 2010;52:413-421.
- 46 Soska KC, Adolph KE, Johnson SP. Systems in development: motor skill acquisition facilitates three-dimensional object completion. *Dev Psychol.* 2010;46:129-138.
- 47 Wilcox T, Woods R, Chapa C, McCurry S. Multisensory exploration and object individuation in infancy. *Dev Psychol.* 2007;43:479-495.
- 48 Kirkham NZ, Wagner JB, Swan KA, Johnson SP. Sound support: intermodal information facilitates infants' perception of an occluded trajectory. *Infant Behav Dev.* 2012;35:174-178.
- 49 Hadders-Algra M. Variation and variability: key words in human motor development. *Phys Ther.* 2010;90:1823-1837.
- 50 Bertenthal B, Von Hofsten C. Eye, head and trunk control: the foundation for manual development. *Neurosci Biobehav Rev.* 1998;22:515-520.
- 51 Hopkins B, Ronnqvist L. Facilitating postural control: effects on the reaching behavior of 6-month-old infants. *Dev Psychobiol.* 2002;40:168-182.
- 52 Bartlett DJ, Chiarello LA, McCoy SW, et al. Determinants of gross motor function of young children with cerebral palsy: a prospective cohort study. *Dev Med Child Neurol.* 2014;56:275-282.
- 53 Kalagher H, Jones SS. Developmental change in young children's use of haptic information in a visual task: the role of hand movements. *J Exp Child Psychol.* 2011;108:293-307.
- 54 Thelen E. Grounded in the world: developmental origins of the embodied mind. *Infancy.* 2000;1:3-28.
- 55 Feldman R, Eidelman AI, Sirota L, Weller A. Comparison of skin-to-skin (kangaroo) and traditional care: parenting outcomes and preterm infant development. *Pediatrics.* 2002;110:16-26.
- 56 Lobo MA, Galloway JC, Savelsbergh GJP. General and task-related experiences affect early object interaction. *Child Dev.* 2004;75:1268-1281.
- 57 Lobo MA, Galloway JC. Postural and object-oriented experiences advance early reaching, object exploration, and means-end behavior. *Child Dev.* 2008;79:1869-1890.
- 58 Lobo MA, Galloway JC. Enhanced handling and positioning in early infancy advances development throughout the first year. *Child Dev.* 2012;83:1290-1302.
- 59 Harbourne RT, Willett S, Kyvelidou A, et al. A comparison of interventions for children with cerebral palsy to improve sitting postural control: a clinical trial. *Phys Ther.* 2010;90:1-18.
- 60 Rocha NA, Tudella E. The influence of lying positions and postural control on hand-mouth and hand-hand behaviors in 0-4-month-old infants. *Infant Behav Dev.* 2008;31:107-114.
- 61 Haumont T, Rahman T, Sample W, et al. Wilmington Robotic Exoskeleton: a novel device to maintain arm improvement in muscular disease. *J Pediatr Orthop.* 2011;31:e44-e49.