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Sucking Behavior in Typical and Challenging Feedings in Association with Weight Gain from Birth to 4 Months in Full-Term Infants

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Abstract

Sucking behavior has been described as an obesity risk marker. Sucking behavior in response to challenge has not been examined as a prospective predictor of infant weight gain. Healthy, full term infants had sucking behavior assessed at ages 2 weeks and/or 2 months via a sucking pressure measurement device in two feeding conditions: during a standard feeding and during a feeding with a more challenging nipple. Weight and length were measured at 2 weeks, 2 months, and 4 months and weight-for-length z-score (WLZ) calculated. Among 45 full term infants, adjusted for age at measurement and time since last feeding, the challenging versus typical feedings differed with regard to amount consumed (54.1g vs. 65.6g, $p<.05$), maximum sucking pressure (121.3mmHg vs. 99.2mmHg, $p<.05$), mean burst duration (17.5s vs. 28.4s, $p<.05$), and feeding duration (18.51 minutes vs. 13.89 minutes, $p<.01$). Grams consumed in the challenging, but not typical, feeding, adjusted for age and time since last feeding, predicted rate of change in WLZ from time of measurement to age 4 months ($r=0.46$, $p=.013$ for challenging, $r=-0.07$, $p=.702$ for

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typical). Nipples that are more challenging to suck from change the sucking behavior and intake among full term infants. Infants who consume more when the nipple is more challenging have greater prospective weight gain. This persistent sucking behavior in the face of challenge may reflect that a greater willingness to work for food, a known obesity risk factor, is detectable in early infancy.

Keywords

Obesity

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1. Introduction

1.1 Weight Gain in Infancy

Obesity is a significant public health problem (Ogden et al., 2018). Preventing obesity is much more effective than treating it (Epstein, Valoski, Wing, & McCurley, 1990, 1994), and once obesity is established it is very likely to persist throughout the lifespan (Freedman et al., 2005; Nader et al., 2006). The rate of weight gain in the first year after birth is a robust risk factor for obesity later in childhood and into adulthood, independent of prenatal factors or birth weight (Baird et al., 2005; Dennison, Edmunds, Stratton, & Pruzek, 2006; Ong & Loos, 2006; Taveras et al., 2011). Preventing rapid weight gain in infancy is an important target for obesity prevention, however, the mechanisms of rapid weight gain in the first year of life are unknown (Lumeng, Taveras, Birch, & Yanovski, 2015). The amount that an infant eats is a likely contributor to differential rates of weight gain. Infants with a vigorous sucking pattern gain more weight in infancy (Agras, Kraemer, Berkowitz, & Hammer, 1990; Agras, Kraemer, Berkowitz, Korner, & Hammer, 1987; Stunkard, Berkowitz, Schoeller, Maislin, & Stallings, 2004). Understanding how vigorous sucking may function as a behavioral marker of obesity risk may contribute to the development of improved obesity prevention strategies in infancy.

1.2 Infant Sucking Behavior

Sucking is one of the most phenotyped features of infant eating behavior and is measured by placing a continuous pressure sensor in a standard nipple (Dubignon & Campbell, 1969; Sameroff, 1968). Much of the work on infant sucking behavior has focused on identifying intervention strategies for infants with difficulties with sucking and feeding (e.g., premature infants (Lau, 2016) or those with cleft palate (Bessell et al., 2011)). This work has therefore focused on the mechanics of sucking as a means of facilitating improved oral feeding performance or greater intake (Lau, 2016; Medoff-Cooper, Shults, & Kaplan, 2009). Less work has focused on features of sucking as early markers of a voracious feeding pattern and obesity risk.

Several studies have described vigorous sucking patterns as linked to greater infant weight gain (Agras et al., 1990; Agras et al., 1987; Stunkard et al., 2004). Prior work with a primarily white cohort of 99 infants evaluated sucking at 2 and 4 weeks of age, with sucking parameters averaged between the two ages (Agras et al., 1990; Agras et al., 1987). In this cohort, among 81 infants followed to age 1 year, longer inter-burst interval was associated

with greater skinfold thickness (Agras et al., 1987) and among 79 infants followed to age 2 years, greater sucking pressure was linked to greater skinfold thickness (Agras et al., 1987). Among 54 of these infants followed to age 6 years, sucking pressure in infancy was correlated with body mass index (BMI) at ages 1, 2, and 3 years with $r=.29$ to $.35$ (Agras et al., 1990). In adjusted analyses, sucking pressure remained a robust predictor of BMI at ages 1, 2, and 3 years, above and beyond other sucking parameters including caloric intake during sucking, feeding duration, and inter-burst interval (Agras et al., 1990). Another group of investigators tested the nutritive sucking behavior of 78 white infants (40 of obese mothers and 38 of lean mothers) at age 3 months (Stunkard et al., 2004). Number of sucks per feeding was greater among infants of obese mothers, with no difference in total feed time. Number of sucks in the feeding also contributed to prospective weight gain and change in skin folds at age 2 years. In a more recent study among 16 infants, a trend was observed such that infants who maintained a higher weight status from birth to age 7–8 months, compared to those who did not, exhibited greater mean sucking pressure (Stough, Bolling, Zion, & Stark, 2018).

Aside from the more recent work with 16 infants, the studies identifying these associations were in two cohorts with a relatively low prevalence of rapid weight gain and now nearly 20 years old. In addition, these studies examined only typical, naturalistic feedings, and did not present the infants with a more challenging feeding scenario, which may have elicited different behavior. We were able to find only one prior study that examined how infants of differing weight status differentially responded to making it more difficult to feed (Nisbett & Gurwitz, 1970). In this study with 34 infants, when sucking was made more difficult (in the same manner employed in our study, using a nipple with a smaller aperture), heavier infants were found to be less willing to exert more effort to obtain food than were lighter infants (Nisbett & Gurwitz, 1970).

1.3 Infant Sucking Behavior as Potential Measure of Food Reinforcement

As reviewed elsewhere (Epstein, LeDy, Temple, & Faith, 2007), a reinforcer is a stimulus that increases the rate of a behavior that it follows and the reinforcing value of food is defined as how much an individual will work to obtain food (i.e., “willingness to work for food”). Dopamine is understood to be the primary neurotransmitter involved in food reinforcement (Wise, 2006). A literature dating back to the 1970’s has reported that individuals with obesity, compared to individuals without obesity, find food more reinforcing (Johnson, 1974; Saelens & Epstein, 1996). This older literature reported that although individuals with obesity, compared to those without obesity, are less willing to work for food in response to caloric deprivation, they are more willing to work for food that has rewarding properties (Schachter, 1968). More recent literature has focused on systematically measuring food reinforcement, its predictors, moderators, and correlates, as well as intervening upon it (Epstein, Lin, Carr, & Fletcher, 2012; Epstein, Yokum, Feda, & Stice, 2014; Kong et al., 2016; Kong, Feda, Eiden, & Epstein, 2015).

The reinforcing value of food has been measured in prior work by tasks requiring the study participant to engage in a repetitive, boring task to obtain a food reward. Individuals (including children) who work longer at a boring and repetitive task to earn a food reward

are more likely to be obese (Hill, Saxton, Webber, Blundell, & Wardle, 2009; Temple, Legierski, Giacomelli, Salvy, & Epstein, 2008). The task employed to measure food reinforcement has typically been playing a boring computer game to earn food (versus non-food) rewards. The nature of the task presents developmental challenges for measurement in early childhood and infancy.

In recent work investigating food reinforcement in infancy, infants aged 9 to 18 months were trained to participate in a slightly modified computer game to earn food versus non-food rewards (Kong et al., 2016; Kong & Epstein, 2016); results of the study confirmed an association between greater relative reinforcing value of food and greater infant weight-for-length z-score, thereby extending the measurement and observation of this behavioral phenomenon and its association with weight to as young as 9 months. To our knowledge, no studies have attempted to measure food reinforcement at a developmental stage that precedes the ability to use fine motor skills to engage in a computer game.

Measuring food reinforcement in early infancy presents challenges. In particular, use of the term “willingness to work” is problematic because it attributes inappropriate volition and potentially even manipulative intent to the behavior. Nonetheless, in early infancy two of the most energetically costly behaviors that might reflect “work” are crying and sucking.

The work of crying requires more than 5 times the energy expenditure of a quiet, alert state (Zeifman, D.M., 2001 and Thureen, P.J., et al., 1998). Infants who are more demanding (i.e., exhibit the work of crying more) have been shown to have greater weight gain in several studies. Masai infants in Kenya who were rated by their mothers as more demanding were less likely to die in a severe drought and famine that occurred several months later (deVries, 1984). In a cohort of more than 5000 9-month-old infants, being described as demanding predicted obesity in early childhood (Peacock-Chambers et al., 2017). Among 75 infants, greater distress to limitations, which included difficulty waiting for food, predicted greater weight gain from birth to 8 weeks (Darlington & Wright, 2006). Among more than 29,000 Norwegian infants, difficult temperament, which was primarily defined by crying and being “demanding”, predicted rapid weight gain from birth to 6 months (Niegel, S. et al., 2007). In summary, engaging in the “work” of an energetically costly behavior – the crying involved in being demanding – predicted greater weight gain.

More so than the work of crying, the work of sucking may be a particularly useful indicator of food reinforcement because it is more directly related to feeding and can be easily quantified. Given that a reinforcer (food) is a stimulus that increases the rate of a behavior that precedes it (in this case, sucking), it follows that infants for whom food has a greater reinforcing value would demonstrate more vigorous sucking for food. Paradigms seeking to measure the reinforcing value of food in older children and adults progressively increase the work necessary to obtain the stimulus (i.e., the individual needs to play the computer game for progressively longer in order to obtain each subsequent reward). An analogous task in early infancy would be to increase the sucking strength or duration necessary to obtain food. In summary, the behavioral trait of “willingness to work” for food may be detectable in early infancy based on changes in sucking vigor in response to a nipple that is more challenging to

suck from. This index of willingness to work for food in infancy may predict rapid weight gain.

1.4 Study Objectives and Hypotheses

Therefore, this study sought to identify, among healthy, full-term infants: (1) changes in sucking behavior that occur when a nipple aperture is smaller and therefore more challenging; and (2) associations between sucking behavior in both typical and challenging feedings with prospective change in weight-for-length z-score (WLZ). We hypothesized that indicators of greater “willingness to work” for food in the face of challenge in early infancy would predict greater prospective increases in WLZ.

2. Methods

2.1 Participants

Infant-mother dyads were recruited from the community. Mothers provided written informed consent for themselves and their infants. The University of Michigan Institutional Review Board approved this study. Inclusion criteria were: (1) Child was born at 37.0 – 42.0 weeks gestation, with weight appropriate for gestational age, and no significant perinatal or neonatal complications. Exclusions were: (1) non-fluency in English in the parent; (2) foster child; (3) mother < 18 years old; (4) medical problems or known diagnosis affecting current or future eating, growth or development; (5) child protective services involvement in the neonatal period; (6) infant does not consume at least 2 ounces in one feeding from an artificial nipple and bottle at least once per week. The exclusion of infants who had not yet taken a feeding from an artificial nipple resulted in the exclusion of few infants. Only 30% of women exclusively breastfeed (no supplemental formula) through the first 3 months of infancy and 16% through 6 months (Centers for Disease Control Division of Nutrition, 2013). Of mothers who breastfeed, 85% express milk and feed the infant from a bottle in the first 4 months of infancy (with most doing so within the first week) (Labiner-Wolfe, Fein, Shealy, & Wang, 2008).

To maximize study enrollment, mother-infant dyads could enroll at age 2 weeks or 2 months, resulting in missing data at 2 weeks for infants who enrolled at 2 months. In addition, not all dyads participated in all protocol elements at a given age. Information regarding data completeness is shown in Table 1.

2.2 Sucking Protocol

To facilitate participation, the protocol took place in the infant’s home. The goal was to offer infants their usual milk (expressed breastmilk or formula) in two conditions at ages 2 weeks and 2 months. Infants vary in their suck frequency and duration in response to flow resistance of the nipple (Colley & Creamer, 1958), which is governed by the size of nipple aperture. Thus, in one condition, termed the “typical feeding”, the infant used a Dr. Brown’s standard neck Level 1 nipple (flow rate of 9.21 mL/min). In the second condition, termed the “challenging feeding”, the infant used a Dr. Brown’s standard neck Ultra Preemie nipple (flow rate of 3.39 mL/min). Thus, the challenging nipple had a flow rate about one third of the typical nipple’s flow rate. Milk flow rates by different nipples have been previously

calculated using standard methods (Pados, Park, Thoyre, Estrem, & Nix, 2015) and confirmed in our laboratory. Overall, our goal was to match the flow rate of the nipple the infant typically used with the flow rate of the nipple used in the typical feeding, and for the challenging nipple flow rate to be approximately one third of the typical nipple flow rate.

The typical feeding always occurred first and on a separate day from the challenging feeding. The mean days between the typical and challenging feeding was 6 (SD 5). Mothers were told, “We’re trying to learn more about how babies’ sucking changes when they use a typical nipple, and how they feed when we change to a preemie sized nipple, which has a smaller opening.” Mothers were asked to feed their infant as they usually would, with a sucking pressure measurement device (see below) attached. Mothers were not blind to which nipple type was being used in each feeding. Mothers were asked to prepare the bottle with the infant’s usual breastmilk or formula in her usual manner. The bottle was weighed before and after the feeding. Mothers alerted the research assistant when infants were hungry and ready to eat, as well as when the mother believed the infant was finished. When the mother indicated that the infant was hungry and ready to eat, the protocol immediately began. Mothers reported the time since the start of the last feeding and the amount consumed at the last feeding. Amount consumed (calculated as post-weight – pre-weight) for the challenging and typical feedings was calculated.

We measured infant sucking behavior using the Neonur (Medoff-Cooper, Shults, & Kaplan, 2009). The Neonur or similar devices that include a pressure transducer in a standard infant bottle have been used in multiple prior studies (Agras, Hammer, McNicholas, & Kraemer, 2004; Agras, Kraemer, Berkowitz, & Hammer, 1990; Agras, Kraemer, Berkowitz, Korner, & Hammer, 1987; Kron, Stein, & Goddard, 1963; Lau & Kusnierczyk, 2001; Medoff-Cooper et al., 2009; Stunkard, Berkowitz, Schoeller, Maislin, & Stallings, 2004). The device samples sucking for the first 2 minutes of each feeding (mean 113 seconds, SD 17). The Neonur provides a continuous record of the negative sucking pressure generated by the infant during the test session. It incorporates a silicone rubber-embedded calibrated capillary for metered flow of nutrient into an otherwise ordinary nipple. The sucking signal is derived from a Cobe pressure transducer embedded in a second tube. A suck is classically defined as a pressure wave inclusive of base to peak amplitude pressure and recovery of pressure amplitude to base; the length of the individual suck cycle can vary (Kaye, 1967). Individual sucks typically occur in clusters, referred to as sucking ‘bursts’. A ‘sucking burst’ is defined as a series of sucks with a short time period (<2 seconds) between sucks (Kaye, 1967). Sucking burst duration is the total time of a single burst meeting suck burst criteria regardless of the number of sucks. *Suck_Detect 9.5.14.3* software, programmed in MATrix LABoratory programming language, was used to transform the pressure wave into sucking parameters. The software employs a set of mathematical and signal processing techniques to detect and classify sucking events in a specific sucking signal. Sampling rate occurred at 250Hz. The lowest detectable pressure for a suck was set at 20 mmHg. Sucking pressure is measured in milliliters of mercury (mm Hg) and time in seconds. Sucking parameters included in this analysis were mean maximum pressure (mmHg) and mean burst duration (seconds).

2.3. Anthropometry

Infants were weighed without clothing or a diaper. Weight was measured on a Tanita Digital Infant Scale in duplicate and averaged. If the weights differed by more than 0.1 kg, the infant was weighed again. Recumbent length was measured using an acrylic Pediatric Stadiometer (Ellard Instruments item# M-PED LB 35–107-X). The infant was aligned in the Frankfort horizontal plane and legs positioned according to standards by Shorr (Shorr, 1984). Length was measured to the nearest 0.1 cm in duplicate and averaged. If measurements were not within 0.2 cm, a third measurement was obtained. All research staff were certified and recertified annually in measurement technique. Weight-for-length z-score (WLZ) was calculated based on the World Health Organization (WHO) Growth Charts (Kuczmarski RJ, 2002).

2.4. Participant Demographics and Feeding History

Mothers reported infant sex, race/ethnicity, and their own highest level of education. Mothers also reported the infant's birthweight as well as birth date and due date, from which gestational age at birth was calculated. At each age point, mothers reported, in the past 7 days, how often the infant was fed formula, breastmilk, and pumped breastmilk. From these data, we calculated the mean number of feedings per day from an artificial nipple in the last 7 days by summing the mean number of formula and pumped breastmilk feedings per day. To calculate the mean proportion of feedings per day over the past 7 days that were from an artificial nipple, we divided the number of formula and pumped breastmilk feedings per day by the number of formula and breastmilk (pumped or fed from the breast) feedings per day. Importantly, the number of artificial nipple feedings per day and proportion of feedings per day from an artificial nipple provide estimates of artificial nipple exposure in the last 7 days, but the duration (in minutes) of daily exposure to an artificial versus natural nipple could not be calculated from the available data. In addition, we were not able to calculate from the available data the infant's lifetime exposure to artificial vs. natural nipple in daily feedings. For descriptive purposes, mothers were also asked if they had ever breastfed, and if they had stopped breastfeeding, at what infant age they had stopped breastfeeding (this infant age was considered zero if the infant had never been breastfed); from these data we calculated breastfeeding duration. For mothers whose infant had consumed any breastmilk in the last 7 days, we also asked if the infant had been fed breastmilk ever from a bottle.

2.5 Statistical Analysis

Analyses were conducted using SAS 9.4 (SAS Institute Inc., Cary, NC). Univariate statistics were used to describe the sample. To test the hypothesis that sucking behaviors would reflect greater challenge when the nipple aperture was smaller, we ran four mixed models accounting for repeated measures within subjects from the main effect of condition (typical versus challenging) and age (2wk and 2 months) predicting: (1) amount consumed, (2) mean maximum pressure, (3) mean burst duration, and (4) duration of feeding. There was no significant interaction of age x condition, and therefore to maximize power we included all measures obtained at either 2 weeks or 2 months in the model. All models were adjusted for age at measurement (2 weeks vs. 2 months) and time since last feeding. To test the hypothesis that indicators that the infant persisted in the face of challenge predict greater

prospective increases in WLZ to age 4 months, we calculated change per month in WLZ from time of measurement (either 2 weeks or 2 months) to age 4 months. If an infant had sucking measured at both 2 weeks and 2 months, we used the 2 week data point in these analyses. We calculated partial correlation coefficients, adjusted for age (2 weeks vs. 2 months) and time since last feeding, for amount consumed, mean maximum pressure, mean burst duration, and duration of feeding, with change in WLZ/month for the challenging and typical feedings individually.

3. Results

Characteristics of the sample are shown in Table 1. Most (89%) of infants had been breastfed at some point. At age 2 months, about 40% of feedings per day were from an artificial nipple and infants took on average 2.2 formula feedings per day. As shown, of the 4 potential protocol elements (typical feeding at 2 weeks, challenging feeding at 2 weeks, typical feeding at 2 months, and challenging feeding at 2 months), 71% participated in 2 of the 4 elements.

As shown in Table 2, the challenging nipple elicited sucking behaviors reflective of greater effort. When the nipple was more challenging, infants consumed less (54.1 (SD 33.4) grams vs. 65.6 (SD 30.0) grams, $p = .03$), sucked with greater mean pressure (121.3 (SD 51.8) mmHg vs. 99.2 (SD 42.1) mmHg, $p = 0.02$), had shorter mean burst duration (17.5 (SD 23.3) sec vs. 28.4 (SD 23.9) sec, $p = .02$), and had longer feeding duration (18.51 (SD 8.45) vs. 13.89 (SD 7.92), $p = .004$). We reran the models in Table 2 further adjusting for the mean number of feedings per day from an artificial nipple, and then reran the models again adjusting for the mean proportion of feedings per day from an artificial nipple. We found no significant change in the results, with the exception that mean burst duration no longer significantly differed between the challenging and typical feedings.

As shown in Table 3, the amount that the infant consumed in the more challenging (but not in the typical) feeding predicted prospective rate of weight gain. No other sucking parameters, in either the typical or challenging feeding, predicted prospective rate of weight gain.

4. Discussion

4.1 Key Findings

This study had several key findings. First, nipples that are more challenging to suck from change the sucking behavior and intake among full term infants. This is consistent with early work on nutritive sucking in full term infants (Sameroff, 1968; Wolff, 1968), but to our knowledge has not been re-examined or described again in the literature in the last 50 years. The second key finding of this study was that infants who consume more when the nipple is more challenging have greater prospective weight gain. We have been unable to identify a prior report of this finding in the literature. This persistent sucking behavior in the face of challenge may reflect that a greater willingness to work for food, a known obesity risk factor, is detectable in early infancy. Overall, our findings are consistent with the hypothesis that infants with greater “willingness to work” for food in the face of challenge in early

infancy have greater prospective increases in WLZ. The mechanism of effect, given that while in the face of challenge, sucking pressure increases, burst duration shortens, but amount consumed still declines, seems to be likely a decline in the volume consumed per individual suck. Future work should investigate this possibility. Nonetheless, the pattern of findings suggests that infants who maintain a large volume of intake per individual suck even when sucking becomes more challenging have future greater prospective rate of weight gain.

4.2 Study Findings in the Context of Prior Work

Our inclusion of an experimental condition in which the infant was faced with a challenge to sucking provides unique information and adds to the prior literature reporting associations between sucking vigor and weight gain (Agras et al., 1990; Agras et al., 1987; Stunkard et al., 2004; Stough, Bolling, Zion, & Stark, 2018). Our study findings differed from the single prior study we were able to identify that examined how infants of differing weight status differentially responded to making it more difficult to feed (Nisbett & Gurwitz, 1970). In that study, heavier infants were found to be less willing to exert more effort to obtain food than were lighter infants (Nisbett & Gurwitz, 1970). This effect was contrary to our findings, which may be due to differences in the study samples or study protocols. Specifically, the study by Nisbett and Gurwitz was conducted in newborn infants, all of whom were formula fed from birth, whereas the cohort of the present study were not newborns and were primarily at least partially breastfed. In addition, it is not possible to determine birthweight or gestational age in Nisbett and Gurwitz's study sample based on the manner in which the data were reported, and there therefore may have been differences in birth weight or gestational age between the samples. In addition, Nisbett and Gurwitz's protocol measured response to a feeding with a larger nipple aperture, then a smaller nipple aperture, and then a larger nipple aperture in sequence on the same day, at feeding intervals determined by the mother. It is notable that the effect of nipple aperture was not found among medium or lower weight infants on either of two days of the study, and the effect of smaller nipple aperture on reducing intake was only found among heavier infants on the second day of two days of study. It is not possible to compare the mechanical characteristics of the nipples employed in each study based on the information provided, but differences in nipple flow may also have contributed to the differences in study findings. Differences in infant caregiving and standards of research reporting that have emerged over the last 50 years present major challenges to comparing current work with the limited prior research.

4.3 Future Directions

The association between sucking vigor and weight in prior work seems to be moderated by characteristics of the feeding such as the sweetness of the solution consumed. Early work showed that infants' birthweight correlated positively with the number of sucks per minute of sweet fluid (but less so for water) (Engen, Lipsitt, & Robinson, 1978). In another early study, heavier infants increased their intake more in response to sweetened formula than lighter infants (Nisbett & Gurwitz, 1970). Thus, future work should examine moderation of associations between sucking vigor and prospective weight gain by characteristics of the milk being fed (i.e., sweetness, breastmilk vs. formula). Future work should also focus on determining if associations between infant weight and willingness to work for food in

response to a smaller nipple aperture are shaped by infant characteristics such as birth weight, gestational age, age at study, breastfeeding status, or caloric deprivation state (i.e., hunger) at the time of the study. Future work will require tight experimental control and modern approaches to measurement of infant adiposity and feeding to identify patterns of association and disentangle the etiology of differences in study findings with confidence. Future work should also consider whether feeding practices moderate associations between infant willingness to work for food in the face of challenge and prospective weight gain. Specifically, it will be important to determine whether maternal feeding practices characterized by careful attunement and responsiveness to infant hunger and satiety cues can mitigate any effect of the infant's robust willingness to work for food on future weight gain. It is possible that willingness to work for food in the face of challenge is a marker for biologically driven hunger, and that caregiving that attunes and responds accurately to the infant's hunger cues may not mitigate links between vigorous sucking in the face of challenge and risk of excessive weight gain. Finally, future work should investigate which sucking parameters, changing in response to which characteristics of the sucking episode, are most predictive of prospective weight gain.

The meaning of the vigorous sucking behavior is unclear. A vigorous sucking style in infancy may be a marker of a fast eating style later in life. Faster eating has been linked with obesity in preschool (Drabman, Cordua, Hammer, Jarvie, & Horton, 1979), and school age (Drabman, Hammer, & Jarvie, 1977) children. More recent work with twins has shown a high heritability of eating rate in children, which is linked with body mass index (Llewellyn, van Jaarsveld, Boniface, Carnell, & Wardle, 2008). A vigorous feeding style has also been found to be more common among mice genetically predisposed to obesity, compared to mice not genetically predisposed (Wilson, Chang, Henning, & Margules, 1981). Future work should consider testing the extent of overlap between vigorous sucking in the face of challenge and features of infant temperament, as it remains unknown if sucking vigor is a marker for an eating-specific behavior, or a more general marker of a temperament characteristic such as persistence.

4.4 Limitations

Interpretation of these findings should note the study limitations. The sample size was small and may not be generalizable to a sample with differing characteristics. There was missing data, which further limited power. We were unable to measure volume consumed per suck with the technology available to us, and this is an important area for consideration in future work. Future work should include larger samples with detailed measurement of exposure to an artificial nipple, which would enable testing of moderation of the effect of nipple type on outcomes by prior artificial nipple exposure. Nonetheless, strengths of this study included the experimental design comparing typical and challenging feedings, and longitudinal cohort follow up.

4.5 Conclusions

In summary, nipples that are more challenging to suck from change the sucking behavior and intake among full term infants and infants who consume more when the nipple is more challenging have greater prospective weight gain. This persistent sucking behavior in the

face of challenge may reflect that a greater willingness to work for food, a known obesity risk factor, is detectable in early infancy.

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Abbreviations

WLZ	weight-for-length z-score
SD	standard deviation

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Table 1.

Sample demographics (n=45)

Variable	N (%) or Mean (SD)
Sex, n (%)	
Female	18 (40.00)
Male	27 (60.00)
Race/ethnicity, n (%)	
Non-Hispanic white	30 (66.67)
Non-Hispanic black	6 (13.33)
Other	9 (20.00)
Maternal education, n (%)	
High school or less	6 (13.33)
Some college	9 (20.00)
4-year college degree or more	30 (66.67)
Gestational age (weeks), mean (SD)	39.61 (1.02)
Birthweight (kg), mean (SD)	3.48 (0.37)
WLZ at 2 weeks, mean (SD)	-0.27 (1.21)
WLZ at 2 months, mean (SD)	0.05 (1.27)
WLZ at 4 months, mean (SD)	-0.05 (1.16)
WLZ per month to age 4 months, mean (SD)	
Any breastfeeding since birth, n (%)	40 (88.89)
Age 2 weeks (n=30)	
Breastfeeding duration in weeks, mean (SD)	1.9 (0.8)
Breastmilk feedings per day, mean (SD)	7.9 (4.6)
Formula feedings per day, mean (SD)	3.1 (3.9)
Age formula introduced in days, mean (SD) n = 17	3.4 (4.2)
Breastmilk ever fed from breast, n(%)	25 (86%)
Breastmilk ever fed from bottle, n(%)	20 (69%)
Number of times fed pumped breastmilk in average week, mean (SD)	10.8 (18.3)
Average number of feedings per day from artificial nipple (formula feedings per day + pumped breastmilk feedings per day)	4.6 (4.6)
Proportion of feedings per day fed from artificial nipple ((formula feedings per day + pumped breastmilk feedings per day)/ (formula feedings per day + breastmilk feedings per day)	0.5 (0.4)
Age 2 months (n=28)	
Breastfeeding duration in weeks, mean (SD)	7.5 (3.4)
Breastmilk feedings per day, mean (SD)	6.0 (4.4)
Formula feedings per day, mean (SD)	2.2 (3.1)
Age formula introduced in days, mean (SD) n = 9	3.3 (2.9)
Breastmilk ever fed from breast, n(%)	22 (79%)
Breastmilk ever fed from bottle, n(%)	21 (75%)
Number of times fed pumped breastmilk in average week, mean (SD)	6.0 (12.0)

Average number of feedings per day from artificial nipple (formula feedings per day + pumped breastmilk feedings per day)	3.1 (3.1)
Proportion of feedings per day fed from artificial nipple ((formula feedings per day + pumped breastmilk feedings per day)/ (formula feedings per day + breastmilk feedings per day))	0.4 (0.4)
<i>Protocol participation</i>	
2 week typical, 2 week challenging, 2 month typical, and 2 month challenging	5
2 week typical, 2 week challenging and 2 month typical	2
2 week typical, 2 week challenging, and 2 month challenging	1
2 week typical, 2 month typical, and 2 month challenging	4
2 week typical and 2 week challenging	11
2 month typical and 2 month challenging	8
2 week challenging and 2 month typical	1
Only 2 week typical	4
Only 2 week challenging	2
Only 2 month typical	6
Only 2 month challenging	1

Table 2.

Mixed models accounting for repeated measures within subjects predicting each sucking parameter from age and feeding condition (n=45)

	Amount consumed (grams)		Mean real maximum pressure (mmHg)		Mean burst duration (seconds)		Duration of feeding (minutes)	
	Adjusted mean (SD)	B (SE)	Adjusted mean (SD)	B (SE)	Adjusted mean (SD)	B (SE)	Adjusted mean (SD)	B (SE)
Feeding Condition								
Challenging	54.09 (33.41)	-11.47 (5.26) *	121.30 (51.75)	22.07 (9.48) *	17.47 (23.28)	-10.89 (4.46) *	18.51 (8.45)	4.62 (1.53) **
Typical	65.56 (29.98)	0.00	99.23 (42.08)	0.00	28.36 (23.86)	0.00	13.89 (7.92)	0.00
Age (2 months vs. 2 weeks)	-	11.59 (6.09) †	-	7.60 (11.80)	-	0.96 (5.62)	-	-1.17 (195)
Time since last feeding (minutes)	-	0.21 (0.05) ***	-	0.20 (0.08) *	-	0.13 (0.04) **	-	0.03 (0.01) ‡

***
p<.001

**
p<.01

*
p<.05

†
p<.10

Table 3.

Partial correlations, adjusted for age at sucking measurement and time since last feeding, of sucking measures with change in weight-for-length z-score per month from time of measurement to age 4 months (n=45)

	Typical Feeding	Challenging Feeding
Amount consumed (grams)	-0.07	0.46*
Mean real maximum pressure (mmHg)	-0.13	-0.08
Mean burst duration (seconds)	-0.15	-0.10
Duration of feeding (minutes)	-0.10	0.08

* p=0.13