Exploring within-task calibration in free-flowing manual sampling in 9-month-olds*

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***Abstract* - Change occurring across multiple timescales, from milliseconds to year-long periods, is inherent to any developmental process. Short-time behavioral fluctuations on the scale of minutes illustrate flexibility and calibration to the environmental context; however, relatively little is known about how such behavior unfolds in less controlled conditions. The current study investigates how infants' manual object sampling movements change within a short, spontaneous, free-flowing play session in a laboratory setting.**

Nine-month-old infants participated in a free-flowing dyadic play session with their caregiver, where they were free to move and interact. The analysis focused on how the duration of a sampling episode with an interactive object (a button-press toy that elicited visual feedback) changed during the 5-minute-long task. A subset of infants (*n* = 51) engaged with the object in at least three separate 30-second windows. Their sampling episodes were categorized into these windows to assess changes in sampling duration over time.

We predicted that infants would sample the object for shorter durations over time, reflecting within-task movement calibration to better match the object's properties. However, contrary to our expectations, a linear mixed model indicated no significant differences in sampling duration, which was around 1 second across the three windows.

These findings suggest that 9-month-old infants maintained a consistent sampling pattern throughout the task, with no major changes in duration. One possible interpretation is that brief, 1-second-long sampling episodes functioned as a behavioral attractor, guided by pre-existing movement strategies suited to the object's properties.

While more research is needed to fully understand how infants adapt their actions in real time, the current study is an initial step in examining within-task calibration in infants' self-initiated manual sampling.

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I. INTRODUCTION

According to the dynamic systems approach, development is a continuous process of change occurring across multiple time scales, from moment-to-moment fluctuations to long-term developmental transitions [1], [2], [3]. Infant behavior is flexible and context-dependent, emerging from the interaction of both internal factors (e.g., movement goals) and external constraints (e.g., objects) [4]. For example, reaching is shaped by motor abilities [5], [6], [7], [8], body position [9], [10], and the physical properties of objects, such as their size [11], [12], shape [13], [14] and texture [15]. Rather than passively responding to externally imposed tasks, infants create their own learning opportunities, generating a self-directed curriculum that aligns with their current needs and abilities. Through spontaneous exploration, they regulate the timing, duration, and variability of their interactions, allowing them to refine movement strategies, test different possibilities, and adapt their actions in ways that best support their development [16].

The variability of behaviors is not merely a byproduct of exploration; it has been recognized not only as an integral part of the learning process [17], [18], [19] but also as a key indicator of typical motor development [20], [21]. Despite prior long-scale studies on variability in domains such as postural control [22], [23] and behavioral fluctuations in infant responses [24], little is known about how infants' spontaneous object interactions fluctuate over short time scales.

Understanding motor variability is particularly important in the study of reaching and object manipulation, where most research relies on standardized tasks with tightly controlled variation (e.g., [5], [25], [26], [27], [28], [29]). In these studies, infants typically do not initiate manual sampling freely; instead, objects are handed or presented to them to reach and handle for fixed durations. This approach stems from the challenge of systematically studying infant behavior due to its variability, which allows them to adapt to their surroundings but also makes research more challenging [30]. Experimental studies address this issue by strictly controlling the setting and variables. While structured environments are crucial for identifying infants' motor capabilities, they do not always capture the variability observed in everyday life [31]. For example, in home settings, infants' movement patterns are highly dynamic - they take thousands of steps per hour, frequently change direction [32], and engage in object sampling through short, time-distributed episodes [33]. While the structured approach is an important method in developmental research, it needs to be complemented by studies in naturalistic environments [34], where object interactions unfold in a more spontaneous and variable manner.

By building on insights from structured research, we can now explore short-term changes in free-flowing activities where infants engage in highly variable, self-initiated object interactions, providing a more comprehensive understanding of their everyday behaviors. Our approach balances the control of structured tasks with the ecological validity of naturalistic observations. While key variables remain controlled, infants are free to adopt various body positions, determine their own sampling durations, and interact with objects with less external constraints, offering a more realistic representation of changes in spontaneous behaviors.

By investigating short-term behavioral calibration, we aim to bridge the gap between micro (milliseconds of biological responses) and macro (months of development) timescales, providing a deeper understanding of behavioral variability in object sampling within a 30-second-long temporal window. We hypothesize that infants will not sample objects for a uniform duration throughout. Instead, we expect longer sampling durations initially, reflecting exploration and familiarization with the object, followed by a decrease in duration as the task progresses, as infants learn about the toy's features and adjust their movements to sample the object more efficiently.

II. METHODS

A. Participants

This study analyzed data from a longitudinal investigation of infant-caregiver interactions (see [35], [36], [37]). The sample included N = 80 (34 girls, 46 boys) typically developing 9-month-old (Mdn = 9, IQR = 0.43) infants from Polish-speaking, middle-class families from a city of over 1.8 million residents. Infants were born full-term (except for one infant born at 35 weeks with typical development) and had no major health or neurodevelopmental concerns reported by their caregivers. Each testing session started with explaining the study protocol to the parent and obtaining written consent. As the parent and infant got familiar with the room, they took part in a series of interactive tasks with different sets of age-appropriate objects (i.e., rattles, puppets, manipulative objects, and books), and the order of the tasks was counterbalanced across participants and testing sessions. The present analysis was focused on one of the tasks - playing with toys that encourage variable manual actions such as reaching, holding, pushing, and pulling actions to explore manipulative objects. The study conformed to the Declaration of Helsinki and received approval from the Ethics Committee at the Institute of Psychology, Polish Academy of Sciences.

B. Procedure

Sessions took place in a laboratory playroom equipped with remote-controlled cameras. Each caregiver-infant dyad engaged in a free-flowing session with four manipulative objects placed near them. Refer to Fig. 1 (a) for the pictures of the objects. For this analysis, we focused on interactions with one toy, shown in Fig. 1 (b), that required pressing a button to trigger an action (ball spinning). This toy measured 21 × 20 × 17 cm and weighed 460 g. Caregivers received no specific instructions and were asked to play as they normally would at home. The purpose of this task was to capture spontaneous interactions with objects within a minimally structured and physically constrained environment. The session lasted approximately five minutes (Mdn = 5.4, IQR = 0.54). The tasks were recorded with three remote-controlled High-Definition cameras (Axis, Inc.), recording at 25 fps, which were placed in three corners of the room.

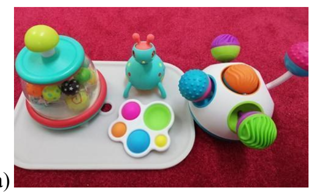
(a)  (b) 

Figure 1. (a) The toys used in the task. In the current paper, only manual sampling on the toy on the far left was analyzed. (b) Full view of the toy used for the analyses.

C. Behavioral annotation

Video recordings were coded in ELAN (Version 6.7) [38]. Following examples from the literature [39], [40], manual object contact was coded from the first to the last frame of contact between the hand of the infant and the object. Right- and left-hand contacts were recorded separately. To assess reliability, 12.5% of participants (n = 10) were double-coded by a second annotator. Cohen's κ, calculated using the Iterative Proportional Fitting method [41], was 0.72, indicating substantial agreement [42]. Further analysis was conducted on sampling episodes made on the target object presented in Fig. 1 (b).

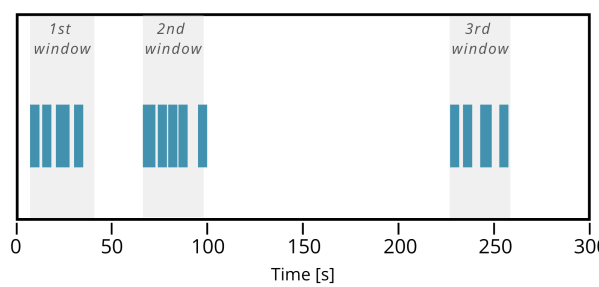


Figure 2. Graphical representation of sampling episodes (blue) and sampling windows (gray shade).

D. Preprocessing and statistical analysis

Data from video coding were pre-processed in Python (v3.11) using in-house scripts incorporating *pandas* [43], *NumPy* [44], and *SciPy* [45] packages. Due to substantial variability in infants' sampling counts (M = 23.38, SD = 21.90, range = 1-115), we grouped episodes into windows rather than treating time as a continuous variable based on the time of occurrence. This allowed for comparisons across infants regardless of how often they sampled and minimized bias from clusters of closely spaced episodes. To categorize *sampling episodes* (i.e., bouts) based on their temporal occurrence, they were assigned to *sampling windows* (Fig. 2), which were periods of time spanning 30 seconds defined dynamically based on the timing of the first observed sampling episode. Each window started from the first recorded sampling episode and ended after 30 seconds. The next window's onset was marked with the episode occurring after the previous window. Episodes were included in a window if they fully fell within its duration or extended no more than 7.5 seconds beyond its boundary (<1% of episodes exceeded the boundary). Participants were included in the analysis if they contributed episodes in at least three unique sampling windows (n = 51). For further analysis, only three out of five consecutive sampling windows were considered, as relatively few participants contributed to at least four unique windows (n = 37). To improve statistical validity, episodes longer than 10 seconds (count = 28, 1.43% of the data) were removed.

To analyze changes in the duration of a sampling episode over time, we computed the median duration of a sampling episode per participant per sampling window. Given that duration data were right-skewed (skewness = 2.44), a log transformation was applied, yielding a skewness value of -0.5.

We fitted a linear mixed-effects model (LMM) using the *lmer* function from the *lme4* package [46] in R Statistical Software [47]. LMM is a suitable statistical method to handle hierarchical data while accounting for individual variability [48]. The model included sampling window (1st, 2nd, 3rd) as a fixed effect:

lmer(MedianDuration_log ~ SamplingWindow+ (1 | id))

Here, *MedianDurationLog* represents the log-transformed median duration of a sampling episode, *SamplingWindow* denotes the grouping variable for when sampling occurred, and (1 | id) accounts for within-participant variability.

III. RESULTS

During the task, 51 infants collectively provided 1,254 (*Mdn* = 20, *IQR* = 22.5) manual sampling episodes, lasting on the median of 0.55 seconds each (*IQR* = 1.6).

The purpose of the analysis was to determine whether infants' duration of a sampling episode changed over time. Sampling episodes were grouped into sampling windows representing the first, second, and third 30-second-long windows in which an infant sampled. This ensured a controlled comparison, regardless of when individual infants began sampling. Fig. 3 presents the distribution of durations of sampling episodes per sampling window.

A linear mixed-effects model revealed that the duration of a sampling episode did not change significantly between windows ($\beta = 0.02$, $t(71) = 0.26$, $p = 0.8$). The intercept was insignificant as well ($\beta = -0.25$, $t(104.87) = -1.11$, $p = 0.27$). The random intercept for infants was low (*SD* = 0.54).

During the first 30 seconds of sampling (i.e., first sampling window), infants sampled the toy on the median of 0.9 seconds (*IQR* = 1.15) per episode. In the second sampling window, this duration decreased to 0.8 seconds (*IQR* = 1.16) before slightly increasing to 0.99 seconds (*IQR* = 1) in the third sampling window.

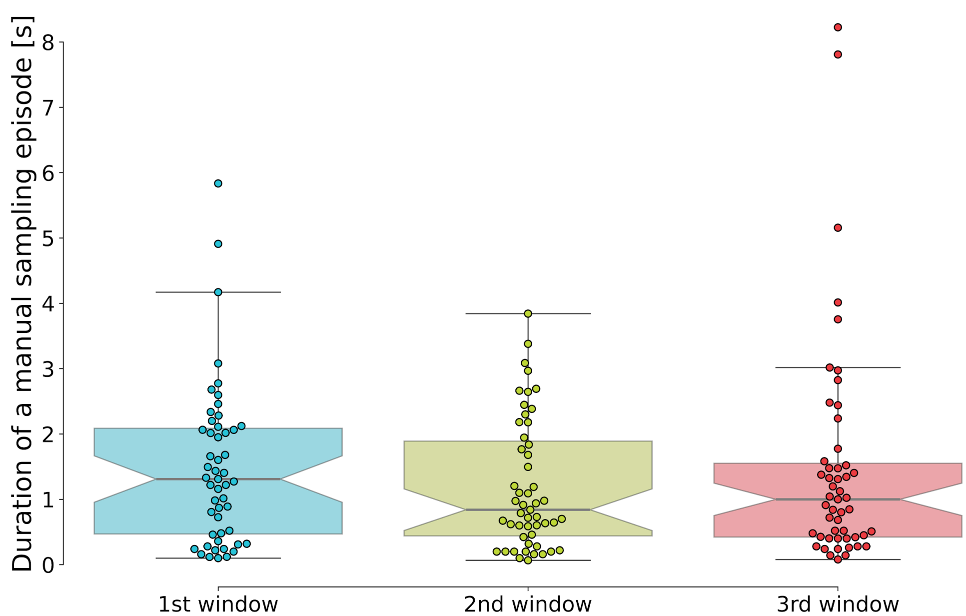


Figure 3. The distribution of the median duration of a sampling episode separated into three sampling windows, each representing a separate 30-second-long period during which the infant sampled. All displayed infants (n = 51) contributed data to all three sampling windows. Each dot corresponds to a participant.

IV. DISCUSSION

This study explored within-task calibration in free-flowing manual sampling, specifically examining whether the duration of infants' sampling episodes changed over time and with repeated contact with the object. We hypothesized that sampling durations would decrease across consecutive sampling windows as infants adjusted their movements to the object's properties and became more efficient in their actions. However, our results did not support this prediction. Instead, infants maintained a consistent sampling duration throughout the session.

Based on the object's properties, we expected a decrease in sampling duration over time. The toy produced a visually appealing response when a button was pressed, which should have encouraged infants to sample it for longer durations initially, allowing them to explore its properties before transitioning to shorter, more goal-directed interactions focused on producing a specific effect (i.e., pressing the button) [49].

Sampling durations remained consistently short (the intercept was not significantly different from zero), around one second per episode for each window, which is considerably shorter than findings from other, more naturalistic studies on infant object sampling indicate [33]. It is possible that the sampling duration was so low that a further decrease would not be physically possible or adaptive. However, this raises the question of why the episodes were so short to begin with. One possible explanation is that 9-month-old infants were producing only brief, exploratory movements, and they were not yet able to adjust their sampling duration to the object's properties, and that such adaptation might only emerge with more repeated experience. However, this explanation seems unlikely given preliminary unpublished results from the same dataset [50]. These findings suggest that during free-flowing manual sampling, 9-month-olds tend to have significantly shorter sampling durations for toys that produce movement or visually appealing reactions upon touch (including the target object in this study) compared to smaller, lighter objects that do not produce any response [50].

Another explanation, consistent with dynamic systems theory, is that infants had already established an optimal sampling strategy suited to the object and maintained a stable approach from the outset. Given that infants engage in extensive manual sampling throughout the day [51], they have numerous opportunities to refine their strategies based on prior experiences with similar objects. These refined behaviors may become well-practiced motor patterns, allowing infants to apply efficient and adaptive solutions even when encountering a new but familiar type of object.

This interpretation aligns with the broader principle that motor learning is a dynamic, self-organizing process shaped by both intrinsic movement tendencies and external constraints. From a dynamic systems perspective, stable yet flexible action patterns, or *synergies*, emerge as infants refine their movements, increasing efficiency while maintaining adaptability [52]. Rather than displaying a linear decrease in sampling durations over time, infants in this study may have been implementing a pre-existing movement pattern that was already well-matched to the demands of the task. The brief, one-second-long sampling episodes observed here may have functioned as a behavioral attractor - a stable and efficient strategy that infants naturally settled into as they interacted with the object [53].

This study represents one of the first attempts to observe gradual calibration within a task, highlighting the need for further research to better understand these processes. Studying within-task, short-term changes in a free-flowing setting is essential for understanding how infants adapt their actions in real-time. The ability to modify movements in response to environmental demands is a key aspect of typical development, while reduced flexibility has been associated with neurodevelopmental conditions such as cerebral palsy and autism spectrum [18], [21]. Furthermore, understanding these processes has direct implications for intervention strategies. Effective therapeutic approaches rely on the principle that structured activities in the present can drive long-term developmental change [54]. Recognizing short-term calibration as an integral feature of learning can inform interventions that support adaptive motor and cognitive development in children.

V. LIMITATIONS AND FUTURE DIRECTIONS

Investigating infants' spontaneous actions in free-flowing conditions provides valuable insights into their skills and adaptations to contextual demands while also raising opportunities for further research.

Firstly, infants were provided with four toys to encourage free play. However, this meant that they could switch between objects, potentially leading to long intervals between sampling episodes on the object analyzed in this study. Nevertheless, this is unlikely to have significantly impacted our findings, as object switching is a natural aspect of infants' exploration [55]. Additionally, by selecting infants who engaged with the object across multiple time windows, we ensured sufficient interaction to capture meaningful within-task calibration.

Secondly, object sampling was coded as physical contact between the toy and the hand. Infants occasionally (accounting for only 3% of the data) sampled one toy with one hand while holding another toy in the other hand. Although unlikely to impact the current results, these dual-hand interactions present an interesting avenue for future research.

Additionally, parental involvement was not controlled for, as it represents a typical aspect of infant development. However, parental influence on play is an important avenue for future research, as understanding how caregivers guide or respond to infant exploration could offer more insights into the social factors shaping early object sampling [56].

Finally, we lack detailed information about the specific behaviors during each sampling episode - e.g., whether shorter episodes reflected goal-directed actions and longer ones general exploration. Although our current focus was specifically on whether infants changed their sampling durations over time, categorizing the nature of their actions is an important next step.

VI. CONCLUSION

In sum, this study represents a first step in examining within-task changes in infants' self-initiated manual sampling in a free-flowing setting. The results suggest that 9-month-old infants engaged with a button-press toy in a relatively consistent manner, showing minimal change in sampling duration across the task. Although this pattern does not align with our initial prediction that sampling durations would decrease as infants calibrated to the object, the consistency in sampling duration may suggest a different strategy. One interpretation is that brief interactions could have functioned as a behavioral attractor - an efficient and stable way for infants to engage with the toy. However, further research on younger infants in similar conditions is needed to reach any definite conclusions.

Overall, further investigation into within-task calibration in free-flowing settings could provide valuable insights into how infants' self-initiated behaviors assemble and change. Gaining insight into moment-to-moment adaptations may contribute to a more nuanced understanding of motor learning and early development.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

The dataset will be available upon request following an embargo period to allow for the finalization of the ongoing longitudinal project. The computer code used in this study is openly available on GitHub: https://github.com/akoziol98/ICDL25 (accessed on 3rd April 2025). Requests to access the datasets should be directed to ptomalski@psych.pan.pl.

REFERENCES

[1] K. E. Adolph, B. I. Bertenthal, S. M. Boker, E. C. Goldfield, and E. J. Gibson, 'Learning in the Development of Infant Locomotion', *Monogr. Soc. Res. Child Dev.*, vol. 62, no. 3, p. i, 1997, doi: 10.2307/1166199.

[2] E. Thelen, 'Motor development as foundation and future of developmental psychology', *Int. J. Behav. Dev.*, vol. 24, no. 4, pp. 385–397, 2000, doi: 10.1080/016502500750037937.

[3] L. B. Smith and E. Thelen, 'Development as a dynamic system', *Trends Cogn. Sci.*, vol. 7, no. 8, pp. 343–348, Aug. 2003, doi: 10.1016/S1364-6613(03)00156-6.

[4] C. T. Kello and G. C. Van Orden, 'Soft-assembly of sensorimotor function.', *Nonlinear Dyn. Psychol. Life Sci.*, vol. 13, no. 1, pp. 57–78, Jan. 2009.

[5] A. B. Cunha, D. D. A. Soares, R. D. P. Carvalho, K. Rosander, C. Von Hofsten, and E. Tudella, 'Maturational and situational determinants of reaching at its onset', *Infant Behav. Dev.*, vol. 41, pp. 64–72, Nov. 2015, doi: 10.1016/j.infbeh.2015.06.003.

[6] L. B. Karasik, C. S. Tamis-LeMonda, and K. E. Adolph, 'Transition From Crawling to Walking and Infants' Actions With Objects and People: Crawling, Walking, and Objects', *Child Dev.*, vol. 82, no. 4, pp. 1199–1209, Jul. 2011, doi: 10.1111/j.1467-8624.2011.01595.x.

[7] K. E. Adolph and C. S. Tamis‐LeMonda, 'The Costs and Benefits of Development: The Transition From Crawling to Walking', *Child Dev. Perspect.*, vol. 8, no. 4, pp. 187–192, Dec. 2014, doi: 10.1111/cdep.12085.

[8] K. E. Adolph and A. M. Avolio, 'Walking infants adapt locomotion to changing body dimensions.', *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 26, no. 3, pp. 1148–1166, 2000, doi: 10.1037/0096-1523.26.3.1148.

[9] G. J. P. Savelsbergh and J. van der Kamp, 'The Effect of Body Orientation to Gravity on Early Infant Reaching', *J. Exp. Child Psychol.*, vol. 58, no. 3, pp. 510–528, Dec. 1994, doi: 10.1006/jecp.1994.1047.

[10] R. P. Carvalho, E. Tudella, and G. J. P. Savelsbergh, 'Spatio-temporal parameters in infant's reaching movements are influenced by body orientation', *Infant Behav. Dev.*, vol. 30, no. 1, pp. 26–35, Feb. 2007, doi: 10.1016/j.infbeh.2006.07.006.

[11] J. Fagard and A. Pezé, 'Age Changes in Interlimb Coupling and the Development of Bimanual Coordination', *J. Mot. Behav.*, vol. 29, no. 3, pp. 199–208, Sep. 1997, doi: 10.1080/00222899709600835.

[12] C. Newman, J. Atkinson, and O. Braddick, 'The development of reaching and looking preferences in infants to objects of different sizes.', *Dev. Psychol.*, vol. 37, no. 4, pp. 561–572, 2001, doi: 10.1037/0012-1649.37.4.561.

[13] P. Rochat, 'Object manipulation and exploration in 2- to 5-month-old infants.', *Dev. Psychol.*, vol. 25, no. 6, pp. 871–884, Nov. 1989, doi: 10.1037/0012-1649.25.6.871.

[14] H. A. Ruff, L. M. Saltarelli, M. Capozzoli, and K. Dubiner, 'The differentiation of activity in infants' exploration of objects.', *Dev. Psychol.*, vol. 28, no. 5, pp. 851–861, Sep. 1992, doi: 10.1037/0012-1649.28.5.851.

[15] E. Gibson and A. S. Walker, 'Development of Knowledge of Visual-Tactual Affordances of Substance', *Child Dev.*, vol. 55, no. 2, p. 453, Apr. 1984, doi: 10.2307/1129956.

[16] L. B. Smith, S. Jayaraman, E. Clerkin, and C. Yu, 'The Developing Infant Creates a Curriculum for Statistical Learning', *Trends Cogn. Sci.*, vol. 22, no. 4, pp. 325–336, Apr. 2018, doi: 10.1016/j.tics.2018.02.004.

[17] J. Fagard and J. J. Lockman, 'The effect of task constraints on infants' (bi)manual strategy for grasping and exploring objects', *Infant Behav. Dev.*, vol. 28, no. 3, pp. 305–315, Sep. 2005, doi: 10.1016/j.infbeh.2005.05.005.

[18] M. Hadders-Algra, 'Variation and Variability: Key Words in Human Motor Development', *Phys. Ther.*, vol. 90, no. 12, pp. 1823–1837, Dec. 2010, doi: 10.2522/ptj.20100006.

[19] D. J. Herzfeld, P. A. Vaswani, M. K. Marko, and R. Shadmehr, 'A memory of errors in sensorimotor learning', *Science*, vol. 345, no. 6202, pp. 1349–1353, Sep. 2014, doi: 10.1126/science.1253138.

[20] M. Hadders-Algra, ‘Variability in infant motor behavior: A hallmark of the healthy nervous system', *Infant Behav. Dev.*, vol. 25, no. 4, pp. 433–451, Jan. 2002, doi: 10.1016/S0163-6383(02)00144-3.

[21] M. Hadders-Algra, ‘Reduced variability in motor behaviour: an indicator of impaired cerebral connectivity?', *Early Hum. Dev.*, vol. 84, no. 12, pp. 787–789, Dec. 2008, doi: 10.1016/j.earlhumdev.2008.09.002.

[22] R. T. Harbourne and N. Stergiou, ‘Nonlinear analysis of the development of sitting postural control', *Dev. Psychobiol.*, vol. 42, no. 4, pp. 368–377, May 2003, doi: 10.1002/dev.10110.

[23] S. C. Dusing and R. T. Harbourne, ‘Variability in Postural Control During Infancy: Implications for Development, Assessment, and Intervention', *Phys. Ther.*, vol. 90, no. 12, pp. 1838–1849, Dec. 2010, doi: 10.2522/ptj.2010033.

[24] C. De Weerth, P. Van Geert, and H. Hoijtink, ‘Intraindividual variability in infant behavior.', *Dev. Psychol.*, vol. 35, no. 4, pp. 1102–1112, Jul. 1999, doi: 10.1037/0012-1649.35.4.1102.

[25] N. E. Berthier and R. Keen, ‘Development of reaching in infancy', *Exp. Brain Res.*, vol. 169, no. 4, pp. 507–518, Mar. 2006, doi: 10.1007/s00221-005-0169-9.

[26] A. Bhat, J. Heathcock, and J. C. Galloway, ‘Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching', *Infant Behav. Dev.*, vol. 28, no. 4, pp. 445–465, Dec. 2005, doi: 10.1016/j.infbeh.2005.03.001.

[27] C. Von Hofsten, ‘Eye–hand coordination in the newborn.', *Dev. Psychol.*, vol. 18, no. 3, pp. 450–461, May 1982, doi: 10.1037/0012-1649.18.3.450.

[28] C. Von Hofsten, ‘Developmental changes in the organization of prereaching movements.', *Dev. Psychol.*, vol. 20, no. 3, pp. 378–388, May 1984, doi: 10.1037/0012-1649.20.3.378.

[29] C. Von Hofsten and K. Lindhagen, ‘Observations on the development of reaching for moving objects', *J. Exp. Child Psychol.*, vol. 28, no. 1, pp. 158–173, Aug. 1979, doi: 10.1016/0022-0965(79)90109-7.

[30] C. S. Tamis‐LeMonda, Y. Kuchirko, R. Luo, K. Escobar, and M. H. Bornstein, ‘Power in methods: language to infants in structured and naturalistic contexts', *Dev. Sci.*, vol. 20, no. 6, p. e12456, Nov. 2017, doi: 10.1111/desc.12456.

[31] K. S. Kretch *et al.*, ‘Sitting Capacity and Performance in Infants with Typical Development and Infants with Motor Delay', *Phys. Occup. Ther. Pediatr.*, vol. 44, no. 2, pp. 164–179, Mar. 2024, doi: 10.1080/01942638.2023.2241537.

[32] K. E. Adolph *et al.*, ‘How Do You Learn to Walk? Thousands of Steps and Dozens of Falls per Day', *Psychol. Sci.*, vol. 23, no. 11, pp. 1387–1394, Nov. 2012, doi: 10.1177/0956797612446346.

[33] O. Herzberg, K. K. Fletcher, J. L. Schatz, K. E. Adolph, and C. S. Tamis‐LeMonda, ‘Infant exuberant object play at home: Immense amounts of time‐distributed, variable practice', *Child Dev.*, vol. 93, no. 1, pp. 150–164, Jan. 2022, doi: 10.1111/cdev.13669.

[34] H. D'Souza and D. D'Souza, ‘Stop trying to carve Nature at its joints! The importance of a process-based developmental science for understanding neurodiversity', in *Advances in Child Development and Behavior*, vol. 66, Elsevier, 2024, pp. 233–268. doi: 10.1016/bs.acdb.2024.06.004.

[35] Z. Laudanska *et al.*, ‘Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers', *Front. Psychol.*, vol. 13, 2022, doi: 10.3389/fpsyg.2022.896319.

[36] Z. Laudańska *et al.*, ‘Changes in the Complexity of Limb Movements during the First Year of Life across Different Tasks', *Entropy*, vol. 24, no. 4, p. 552, Apr. 2022, doi: 10.3390/e24040552.

[37] A. Kozioł *et al.*, ‘Motor Overflow during Reaching in Infancy: Quantification of Limb Movement Using Inertial Motion Units', *Sensors*, vol. 23, no. 5, p. 2653, Feb. 2023, doi: 10.3390/s23052653.

[38] H. Sloetjes and P. Wittenburg, ‘Annotation by category-ELAN and ISO DCR', in *European Language Resources Association (ELRA)*, 2008.

[39] K. de Barbaro, C. M. Johnson, D. Forster, and G. O. Deák, ‘Sensorimotor Decoupling Contributes to Triadic Attention: A Longitudinal Investigation of Mother-Infant-Object Interactions', *Child Dev.*, vol. 87, no. 2, pp. 494–512, Mar. 2016, doi: 10.1111/cdev.12464.

[40] C. Yu and L. B. Smith, ‘Hand–Eye Coordination Predicts Joint Attention', *Child Dev.*, vol. 88, no. 6, pp. 2060–2078, Nov. 2017, doi: 10.1111/cdev.12730.

[41] S. E. Fienberg and S. Wasserman, ‘An Exponential Family of Probability Distributions for Directed Graphs: Comment', *J. Am. Stat. Assoc.*, vol. 76, no. 373, p. 54, Mar. 1981, doi: 10.2307/2287039.

[42] N. Gisev, J. S. Bell, and T. F. Chen, ‘Interrater agreement and interrater reliability: Key concepts, approaches, and applications', *Res. Soc. Adm. Pharm.*, vol. 9, no. 3, pp. 330–338, May 2013, doi: 10.1016/j.sapharm.2012.04.004.

[43] W. McKinney, ‘Data structures for statistical computing in python', in *Proceedings of the 9th Python in Science Conference*, 2010, pp. 51–56.

[44] C. R. Harris *et al.*, ‘Array programming with NumPy', *Nature*, vol. 585, no. 7825, pp. 357–362, Sep. 2020, doi: 10.1038/s41586-020-2649-2.

[45] P. Virtanen *et al.*, ‘SciPy 1.0: fundamental algorithms for scientific computing in Python', *Nat. Methods*, vol. 17, no. 3, pp. 261–272, Mar. 2020, doi: 10.1038/s41592-019-0686-2.

[46] D. Bates, M. Mächler, B. Bolker, and S. Walker, ‘Fitting Linear Mixed-Effects Models Using **lme4**', *J. Stat. Softw.*, vol. 67, no. 1, 2015, doi: 10.18637/jss.v067.i01.

[47] R Core Team, *R: A language and environment for statistical computing. R Foundation for Statistical Computing*. (2021). Vienna, Austria. [Online]. Available: https://www.R-project.org/

[48] D. H. Spieler and E. Schumacher, *New methods in cognitive psychology*. in Frontiers of cognitive psychology. New York, NY: Routledge, 2020.

[49] L. Fetters and J. Todd, ‘Quantitative Assessment of Infant Reaching Movements', *J. Mot. Behav.*, vol. 19, no. 2, pp. 147–166, Jun. 1987, doi: 10.1080/00222895.1987.10735405.

[50] A. Kozioł, Z. Laudańska, H. D'Souza, and P. Tomalski, ‘Towards less controlled infancy research: real-time interaction between body position and object type in 9-month-olds during self-initiated, free-flowing manual sampling', *Unpublished*, n.d..

[51] M. S. Swirbul, O. Herzberg, and C. S. Tamis-LeMonda, ‘Object play in the everyday home environment generates rich opportunities for infant learning', *Infant Behav. Dev.*, vol. 67, p. 101712, May 2022, doi: 10.1016/j.infbeh.2022.101712.

[52] E. C. Goldfield, B. A. Kay, and W. H. Warren, ‘Infant Bouncing: The Assembly and Tuning of Action Systems', *Child Dev.*, vol. 64, no. 4, p. 1128, Aug. 1993, doi: 10.2307/1131330.

[53] P. Hiver, ‘Attractor States Student Engagement View project Complexity and Dynamic Systems Theory for Second Language Development View project', 2014, doi: 10.13140/RG.2.1.2501.8722.

[54] E. Thelen, ‘Dynamic Systems Theory and the Complexity of Change', *Psychoanal. Dialogues*, vol. 15, no. 2, pp. 255–283, Apr. 2005, doi: 10.1080/10481881509348831.

[55] O. Herzberg, K. K. Fletcher, J. L. Schatz, K. E. Adolph, and C. S. Tamis‐LeMonda, ‘Infant exuberant object play at home: Immense amounts of time‐distributed, variable practice', *Child Dev.*, vol. 93, no. 1, pp. 150–164, Jan. 2022, doi: 10.1111/cdev.13669.

[56] J. L. Schatz, C. Suarez‐Rivera, B. E. Kaplan, and C. S. Tamis‐LeMonda, ‘Infants' object interactions are long and complex during everyday joint engagement', *Dev. Sci.*, vol. 25, no. 4, p. e13239, Jul. 2022, doi: 10.1111/desc.13239.