Exploration in the presence of mother in typically and non-typically developing pre-walking human infants

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Abstract

Using an arsenal of conceptual, computational and statistical tools previously developed for the study of origin-related exploration in animals, we compared exploration of human pre-walking Typically-Developing (TD) and Non-Typically Developing (NTD) infants in the presence of mother. We found that while the TD infants exhibited a highly mother-centered organization involving excursions from mother and back to her, and deep engagement with mother when visiting her, the NTD infants tended to avoid mother's place, performing few, if any excursions, and exhibiting shallow engagement with mother. Given the pervasiveness of origin-related exploration in invertebrates, vertebrates, and primates, it would now be a challenge to find an animal model that would exhibit active exploration while ignoring or suppressing the return to the origin, be it a mother or any other safe haven.

Main

In this study we search for the generative rules that shape the path traced by human pre-walking infants in moment-to-moment exploration of a novel environment, under the protective attention of the infant's relatively stationary mother. Our perspective includes three traditionally distinct fields of study, that of animal exploratory behavior, that of primate, and that of human mother-infant interaction.

A conspicuous spatial regularity in the exploratory behavior of many organisms is a reference place in relation to which they explore the environment. In the wild, many animal species have a home site to which they return regularly after exploring their home range or territory, be they, e.g., wolves[1], small mammals[2], ants[3] bumble bees[4], or millipedes[5]. In behavioral neuroscience experiments, rats explore the experimental arena from a reference place, from which they perform excursions or forays into the environment[6]. High dwell time accumulated through a large number of visits also

characterizes the reference place of, e.g., mice[7], zebra fish[8,9] and infant rats[10]. This reference place, often termed a "home base", exerts its influence on the organism's behavior across the whole exploratory basin. Visits at the home base partition the path into excursions in the environment. The latter are further partitioned into progression segments and staying-in-place (lingering) episodes[11]. In moment-to-moment behavior in a novel environment the excursions grow in extent[12], and differentiate from simple to complex[12].

The performance of exploratory excursions has also been reported in the wild in infant primates – rhesus monkeys[13], baboons[14], and chimpanzees[15]. As the infants of these primates develop, they execute increasingly longer forays from mother into the environment and back to mother. While the mother is often on the move during the performance of such excursions, the excursions nevertheless involve both exploration and active management of distance in reference to an origin or base, by the infant, be it a mobile mother.

Origin-related exploration has also been described in human infants: linking Bowlby's attachment theory to ethological data, Ainsworth observed that human infants "tend to explore on their own initiative an unfamiliar room in their mother's presence, and in doing so use mother as a secure base"[16,17]. Similarly, Mahler's psychoanalytic separation-individuation theory on the psychological development of the human infant is largely supported by observations of the infants' "incessant wondering away" and "checking back to mother", using mother as reference and "home base"[18]. Human infant performance of increasingly longer exploratory excursions from a stationary mother has also been reported[19] previously, and in one study also plotted[20].

The majority of infant mother-related exploration studies consist of verbal reports of behavior, or reports of inferred intrapsychic processes, such as symbiosis[18], separateness[20], identity[21], self, object relationships, or separation anxiety[17], at a day-by-day or month-by-month developmental scale[19,22], whereas the current report is a study of the kinematics at the moment-by-moment actual-genesis scale, allowing a computational comparison of the generative rules that shape the organism's path across taxonomic groups.

The current study is aimed at formulating some of the generative rules that shape mother-related exploration in pre-walking human infants using a description that discloses the infants' engagement with the environment surrounding it. To obtain a wider perspective on the behavior of Typically-Developing (TD) infants, we compared their behavior to that of six Non-Typically Developing (NTD) infants who applied to the Mifne Center for the Treatment of Autism - three infants were referred for developmental assessment by expert clinicians and three infants were referred for treatment by pediatric neurologists. All the NTD infants had primary assessment due to parental concerns regarding their infants' development.

A byproduct of this comparison would be to highlight behavioral symptoms that could later be looked for in prospective animal models of the NTD infants.

Surprisingly, we found that origin-related exploration, prevalent in both vertebrates and arthropods, was weak or even absent in the NTD infants. While this comparison should clearly be repeated in large groups, followed by testing for neurodevelopmental disorders at later ages, our results provide a comparative ethological perspective, and a glimpse into the distinct operational worlds of the TD and NTD infants and into the ways in which they attend and come to grip with the world.

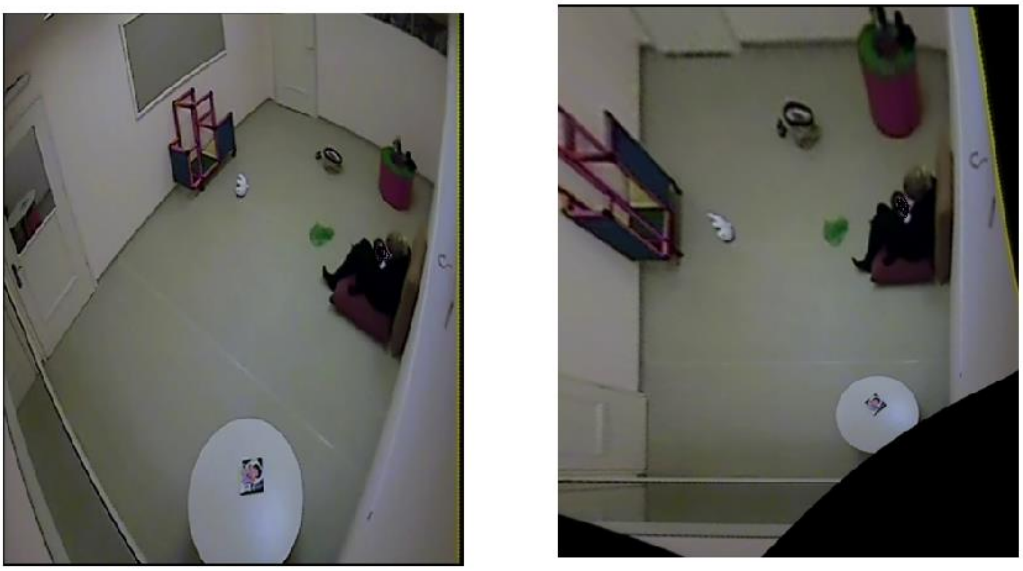

Figure 1. The Mifne Treatment room image, before (left) and after transformations (right). Note furniture, toys, mother's location (here with infant sitting on her lap), on the right side

near the wall), and two doors (on the left – door leading out of the room and on top door leading to bathroom).

Dwell time distribution across the room

This study has been conducted on pre-walking infants at the stage of stable crawling. Infants were recruited with their respective mothers to participate in a videotaped half hour session conducted in a medium-sized room. On each trial the mother entered the room carrying her infant, sat on a mattress in the periphery of the room and then seated the infant or let it slide down next to her. The mother has been requested to remain seated and allow the infant to act freely for a 30 minutes session. 2 video cameras were used across the session, one obtaining a view of the whole room including the infant and the mother (fig. 1), and another zooming on the infants and following them. The behavior of the infant and the mother was videotaped and then tracked for half an hour, a period found to be appropriate in our preliminary study (see methods).

Figures 2a, b present for both the TD and NTD infants the smoothed cumulative dwell time spent in different locations across the observation room, and the number of visits paid by them to neighborhood locations exhibiting peak dwell times (see *Methods*). Dwell time is represented by colored contour lines forming a topographical map. A comparison of, e.g., the TD infant Alon to the NTD infant Tom (all names provided in this paper are fictitious), reveals that in both, dwell time forms a patchy distribution across the room. But whereas for Alon there is a single peak which stands out in terms of dwell time (signified by a yellow center), located near mother, for the NTD infant Tom there are two peaks of relatively the same dwell time and both are located away from mother. Alon spends time over the whole room whereas Tom adheres to the upper half, hardly lingering in the lower half of the room. These differences apply to most of the infants in the respective groups: all TDs have a single preferred place in terms of dwell time whereas NTDs except for two (Yuri and Dean) have more than one peak dwell time place. In all TDs except for one (Alexey, who exhibits several NTD features; see method's section), the peak dwell time place is located by mother, whereas in all NTDs the maximal peak is located away from mother.

Whereas the TD infants tend to establish preferred places also near furniture (Alon by the cabinet, table, and basket, Omri by the cylinder and table, Yoram and Dan by the cylinder, and Alexey by the cabinet and the exit door), the NTDs often establish places away from walls and from the furniture. Five of the NTD infants (Evyatar,

Tom, Dean, Yuri, and Shuval) establish peak dwell time places in the open space facing their mother without proceeding to her. One NTD infant (Shuval), and one TD (Alexey), establish peak dwell times *vis-à-vis* the door leading out of the room, perhaps disclosing an intention to leave the room.

While the TDs tend to cover the whole room (including Dan whose extended staying with mother dwarfs other staying in place episodes across the room; see slso animations), the NTDs tend to adhere to part of the room (See *endpoints summaries* - % room covered): Adva adheres to about a third of the room, completely ignoring the other parts; Dean adheres to the center part of the room vis-à-vis mother, ignoring all the other parts; Evyatar first stays in the lower part of the room and then spends all his dwell time for peak durations in a shoe-shaped strip vis-a-vis mother, ignoring the rest of the room; Shuval ignores the eastern half of the room. Of the NTDs only Yuri covers most of the room and this is due to chasing a rolling large ball for most of the session.

Visits distribution across high dwell time places: Figures 2a, b also provide a spatiotemporal summary of the process by which dwell time has been *allocated* across the session to the main places. The stars, drawn on top of the peak places, represent the number, order, and durations of the visits to the respective peak dwell-time places. Starting at 12 o'clock, the circumference represents the session's half-hour duration. Proceeding clockwise, each wedge presents a visit at this location, with its starting and ending times given by the orientation and therefore its duration presented by the arc's length. For very short visits the wedge appears as a single spoke. Almog, for example, visited the most preferred place by his mother 14 times, thus paying the highest number of visits to the place near mother , and accumulating time near mother in a piecemeal manner, whereas Dean visited his most preferred place only 3 times, ignoring that place for a third of the session. Dean mother's place was visited only twice. These differences in visits managements apply between most of the two groups: all TDs except for Alexey (whose peak visiting place is the doorway leading out of the room) visit the place near mother for the highest number of times; all NTDs top visited places are located away from mother and are each typically ignored for substantial parts of the session. In short, the NTD infants do not show sustained attention, expressed in spread-across-the-session visits, to any place, or object. In both groups visits to most places (except the TD infant mothers' places) are sparse and not

evenly distributed. Both Alexey (TD, but see *methods*) and Shuval (NTD) pay the highest number of visits to the doorway leading out of the room.

It should be noted that the number of visits to peak dwell-time places does not exhaust the number of visits to mother; these visits merely refer to one or at most two places in her vicinity. The infant might, and indeed does, visit mother's vicinity from different directions, dwelling at different locations that do not necessarily take place at a peak dwell time place. Since visits are attributed in this section to peak dwell time places, they do terminate and start excursions from mother's vicinity into the room, but they do not start and end *all* the excursions from mother into the room.

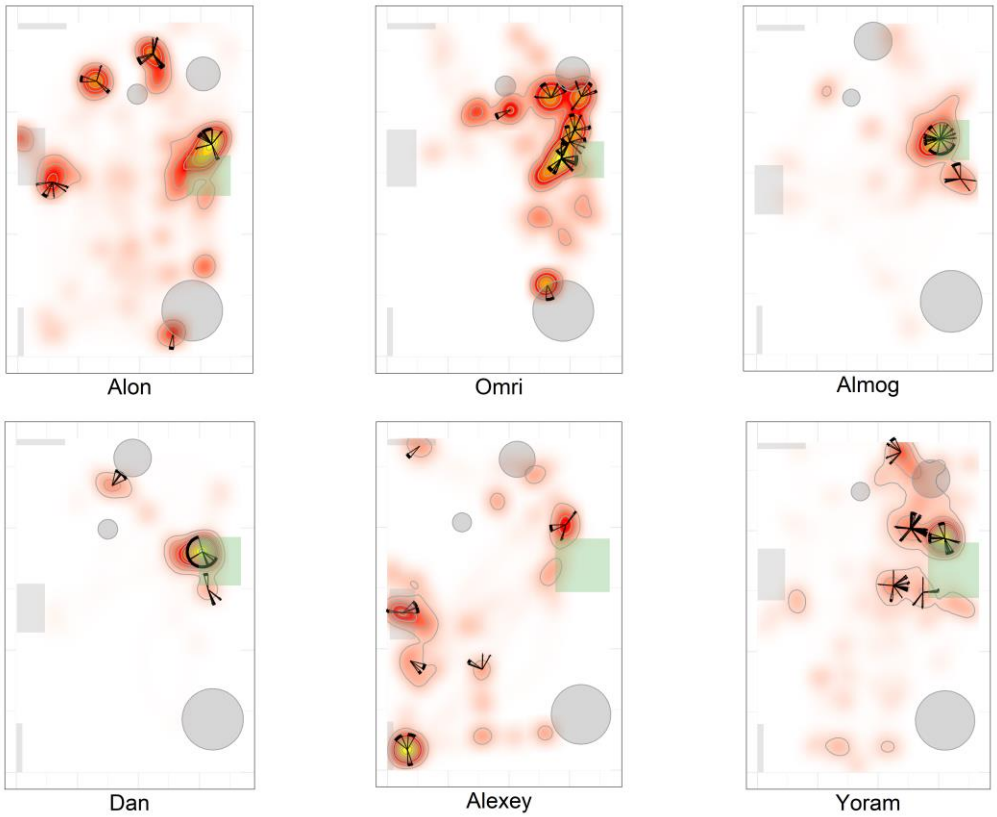

Figure 2 a. The TD infants' most preferred place was located near mother and the infants visited this place regularly paying to it the highest number of visits. The figure presents the smoothed cumulative dwell time spent in different locations across the observation room, and the number of visits paid by the infants to neighborhood locations exhibiting peak dwell times. Number of visits is obtained using the two co-centric circles method ($r_{in} = 30cm$, $r_{out} = 50cm$, see *methods*). Dwell time is represented by colored contour lines forming a topographical map. The contour lines are spaced at the quantiles (0.1, 0.2, 0.3, …) of the smoothed cumulative dwell time (see *methods*). Note that in these heat maps the color is proportional to the dwell time of each specific infant.

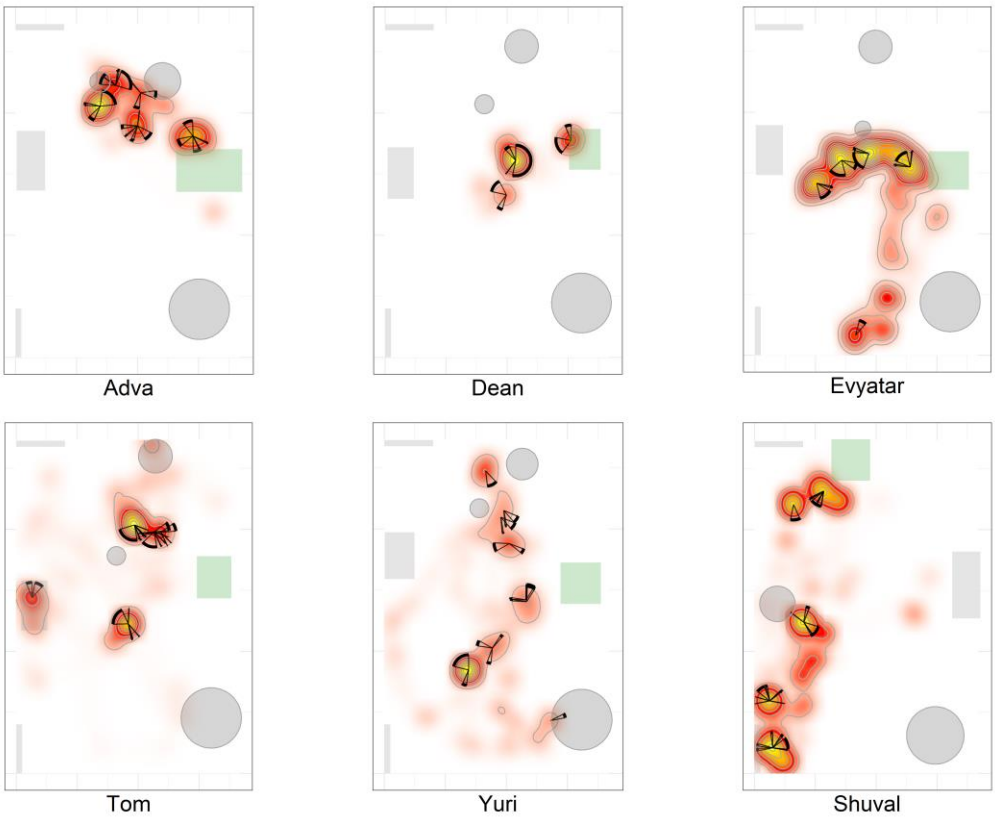

Figure 2 b. The NTD infants' most preferred places are not located near mother and the infants do not visit these places regularly not necessarily paying to them the highest number of visits. For further explanation see figure 2a.

The stable preference of the place located near the mother of the TD infants and the absence of a place having these features near the NTD infants' mother (fig. 2a, b) marks the significance of the TD mothers' location for the behavior of the TD infants thus justifying an examination of all the infants path-sessions in explicit reference to mother's location (See *endpoints summaries* - # of excursions and % time spent near mother).

The itinerary, duration, and extent of engagement of the infants' visits to mother.

By plotting in proper order, across the whole session, the relative time of start, the relative time of end, the duration in session percentages, and the extent of each entry of the infant into mother's proximity we characterize the infants' engagement with the mother: did the infant merely approach mother during a specific visit? Did they touch her? Did they climb on her (see *methods*)? As shown, Alon (fig. 3a) visited mother some 12 times, at times only approaching her and at other times climbing on her, whereas Tom (fig. 3b) spent the first few seconds, at the very start of the session near mother and then barely approached her three more times. More generally, five of the TD infants (Alon, Omri, Yoram, Almog and Dan) came to close, extended, and

persistent grips with mother, whereas all the NTD infants either avoided mother's proximity (Tom and Yuri), or avoided visiting mother for extended parts of the session (Dean, Evyatar and Shuval). Adva, an NTD infant, did visit mother, if only for four visits. Note in 5 TD (Alon, Omri, Almog, Dan and Yoram) and 2 NTD (Adva and Dean) infants the last extended visit which involved, using Mahler's description[18], "melting into mother". The difference in the extent of engagement with mother is also evident in the plots presented in figure S1 of both the average percent time spent, and in the number of visits paid to mother at distances starting from zero centimeters from the center of her location (fig. S1).

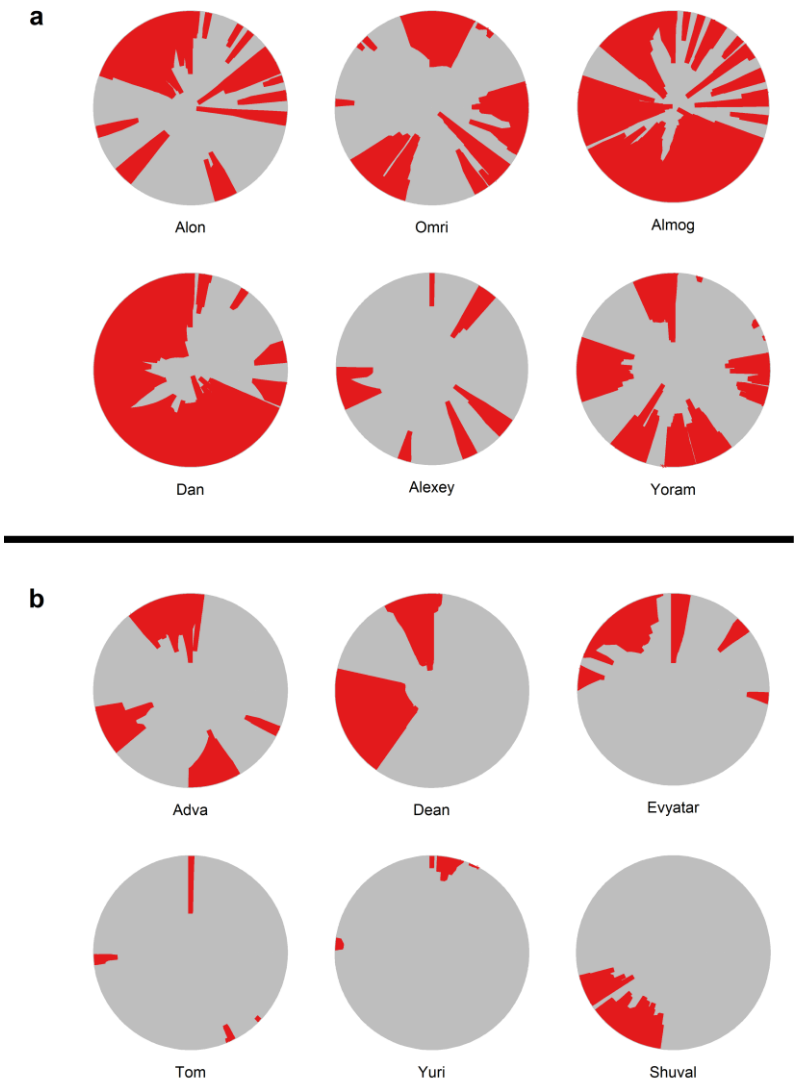

Figure 3. The TD infants (a) visit mother frequently and persistently, invading her place deeply and for long durations, whereas the NTD infants (b) visit mother rarely if at all; when visiting they typically merely approach and do not touch mother. The engagement plots exhibit the timing, duration, and extent of the infant's being in gear with mother. The concentric circles are centered on the center of mother's location, spanning a radius of hundred cm around that center. Starting at twelve o'clock and proceeding clockwise for the session's duration, the arc traced on the circle's circumference and the colored section of the circle, designate the times of start, end, and duration, and the extent of the entry into mother's proximity.

The itinerary, duration, and extent of engagement of the infants' visits to furniture in the room.

Figure 4a, b present plot summaries of the extent of engagement of each of the infants with mother, with the 4 pieces of furniture present in the room, and with the two doorways leading out of the room: how each of the infants moves into grip with structures in the environment, and to what extent do the infants move into grip with mother.

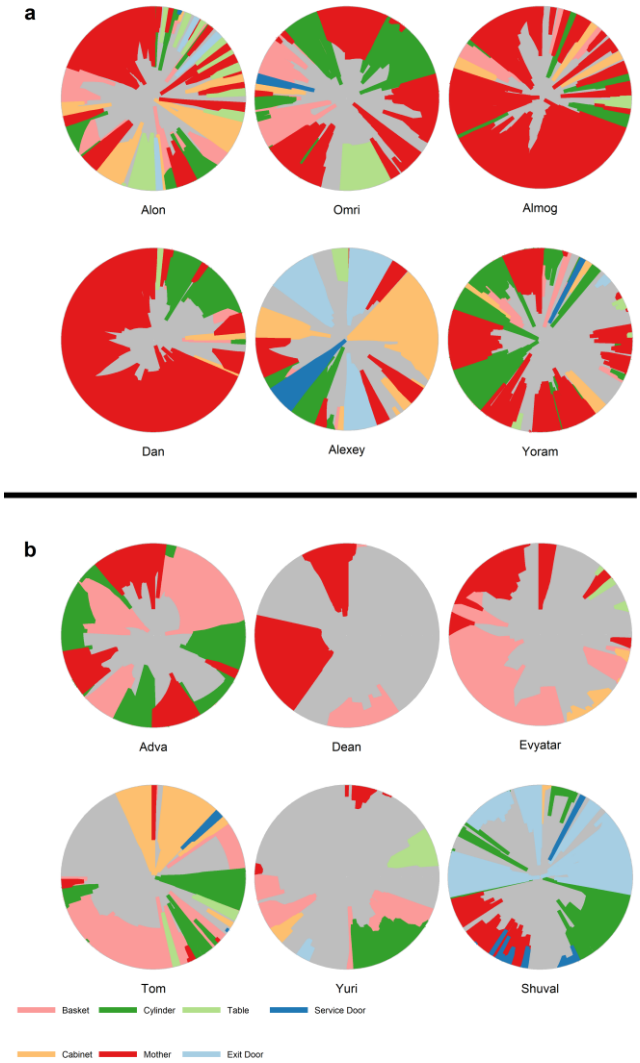

Figure 4. The TD infants visited mother (in red) and the furniture (basket in pink, cylinder in green, table in light green, service door in blue, cabinet in brown, exit door in light blue) frequently and persistently, invading their respective places deeply and for long durations. **b** The NTD infants visits to mother and to the furniture were infrequent and shallow. For explanation of graphs see legend of figure 3.

As in figures 3a, b, starting at 12 o'clock and proceeding clockwise, all the visits paid by each of the infants to these furniture are plotted in their order of performance, including the relative start and end times, and the extent of invasion exhibited in each of the visits. Generally speaking, the TD infants' engagement agendas were much more eventful and dynamic than those of the NTD infants (evidenced by the number and variety of colored sections tiling the circles: multiple sharp spikes that touch the center in TDs (Almog, Dan and Alon) versus few extended sections of few colors that did not reach the center at all in NTDs (Adva, Dean, Evyater and Yuri). i) The TD infants visited multiple furniture paying multiple visits to each, whereas the NTD infants visited the furniture much less frequently. ii) As evidenced by the extent of colored areas near the circles' centers, the TD infants approached and often invaded the furniture whereas the NTD infants tended to approach the furniture less closely and engaged them less deeply. iii) The large grey empty spaces in the NTD engagement graphs disclose the tendency of the NTD infants to sometimes adhere to places that were away from the furniture, either engaging in stereotypies or engaging with a toy, or perhaps attending to themselves rather than to the environment. Adva was exceptional in the NTD group in visiting mother at regular intervals, if only for four visits. Two infants, Alexey and Shuval, paid multiple visits to the doorway leading out of the room, trying to open it, perhaps intending to get out of the situation. The engagement graphs also highlight significant differences within groups: e.g., while Almog alternated between visits to mother and single visits to an object across the session, Alon visited several pieces of furniture between successive visits to mother; The TDs took longer rests at mothers, whereas the NTDs took long rests near furniture.

The infants' management of distance from mother.

We parse the infant's path into excursions by using the zero crossing of the infant's path with the horizontal line marking the boundary occupied by mother's customized place (see *Methods*). In this view, touching, or crossing the line on the way down and on the way up, define a visit to mother. A segment of the path located above the horizontal line and bounded by two zero crossings defines an excursion. As demonstrated in figure 5a, the most noticeable feature of the TDs exploratory path is its partitioning into excursions. Four of the TD infants (Alon, Almog, Dan and Yoram) start the session with short duration excursions (marked by sharp peaks) and

proceed to excursions involving extended lingering episodes (marked by flat-topped peaks). All (except Alexey) end the session by cuddling on mother's lap.

In contrast, the NTD infants (fig. 5b) perform very few if any excursions from mother (the median difference is 9 Wilcoxon rank test p-value 0.005). Adva does perform four excursions ending up on mother's lap; Dean does not visit mother for most of the session, climbing on her lap for nursing only during the last part of the session, Evyatar starts the session with two excursions, but then avoids mother until the end of the session when he climbs her and nurses; Tom establishes a place at a distance, vis-à-vis mother, which he visits several times, sitting there, facing mother, and performing stereotypic behavior without approaching her – as though there is an invisible glass wall between them; Yuri starts the session with three incipient excursions (not captured by the algorithm) and then avoids mother for the whole session, chasing a ball, and ending the session by lingering on his belly while crying in the middle of the room; and Shuval stays at a distance from mother for half of the session, visits mother only twice during the second half of the session, and spends a lot of time near the doorway that leads out of the room, ending the session by crying at the doorway.

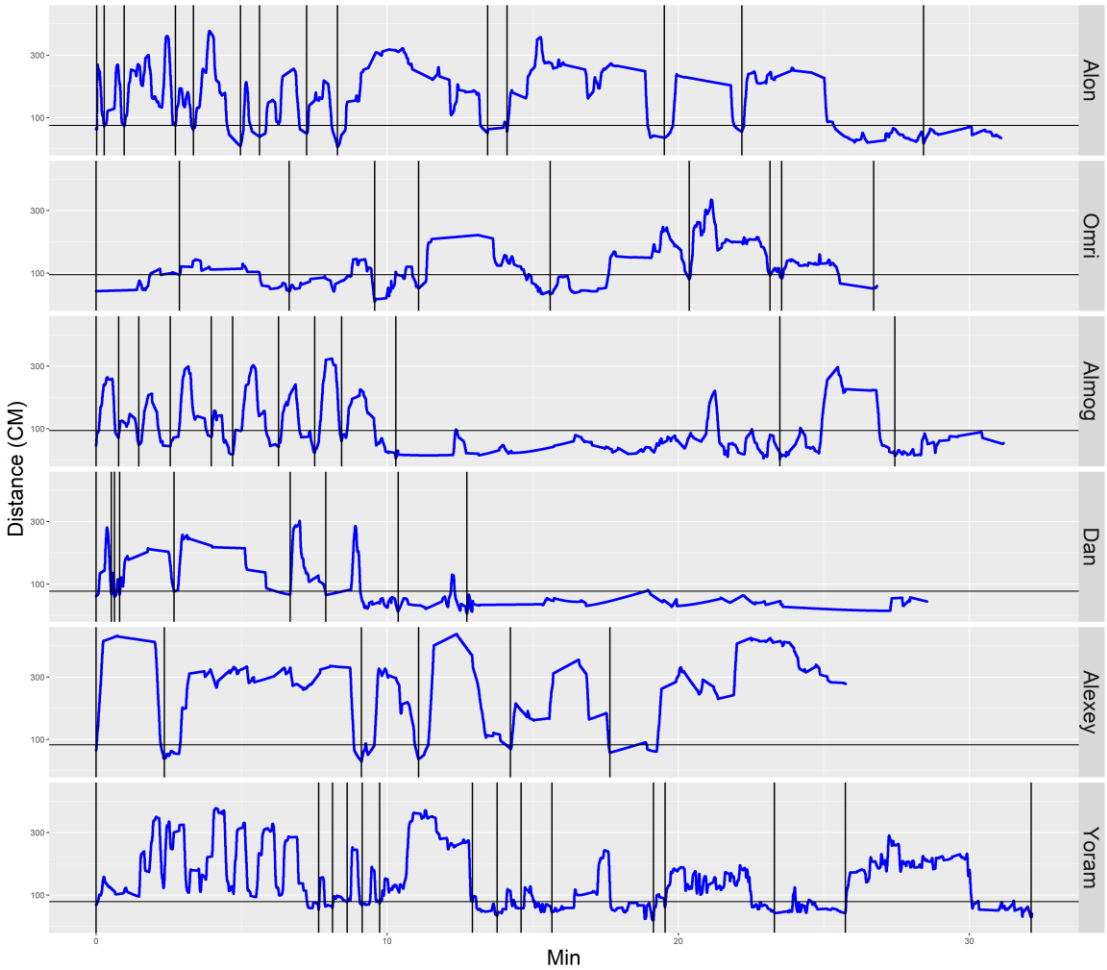

Figure 5 a. A plot of the TD infants' management of distance from mother highlights the multiple, repetitive outbound-inbound motion, the extent of engagement with the mother (sections below the horizontal line), and a tendency to start the session with sharp peaks (short durations of staying at the far end of excursions) and commence with flat-topped peaks (extended durations of staying at the far end of excursions; Alon, Almog, Dan and Yoram). Alexey, exhibiting several features of the NTD infants, is an exception, starting the session with an extended flat-topped peak (see *Methods*). Blue line plots distance from mother, black horizontal line marks mother's customized boundary and black vertical lines segment the plot into excursions.

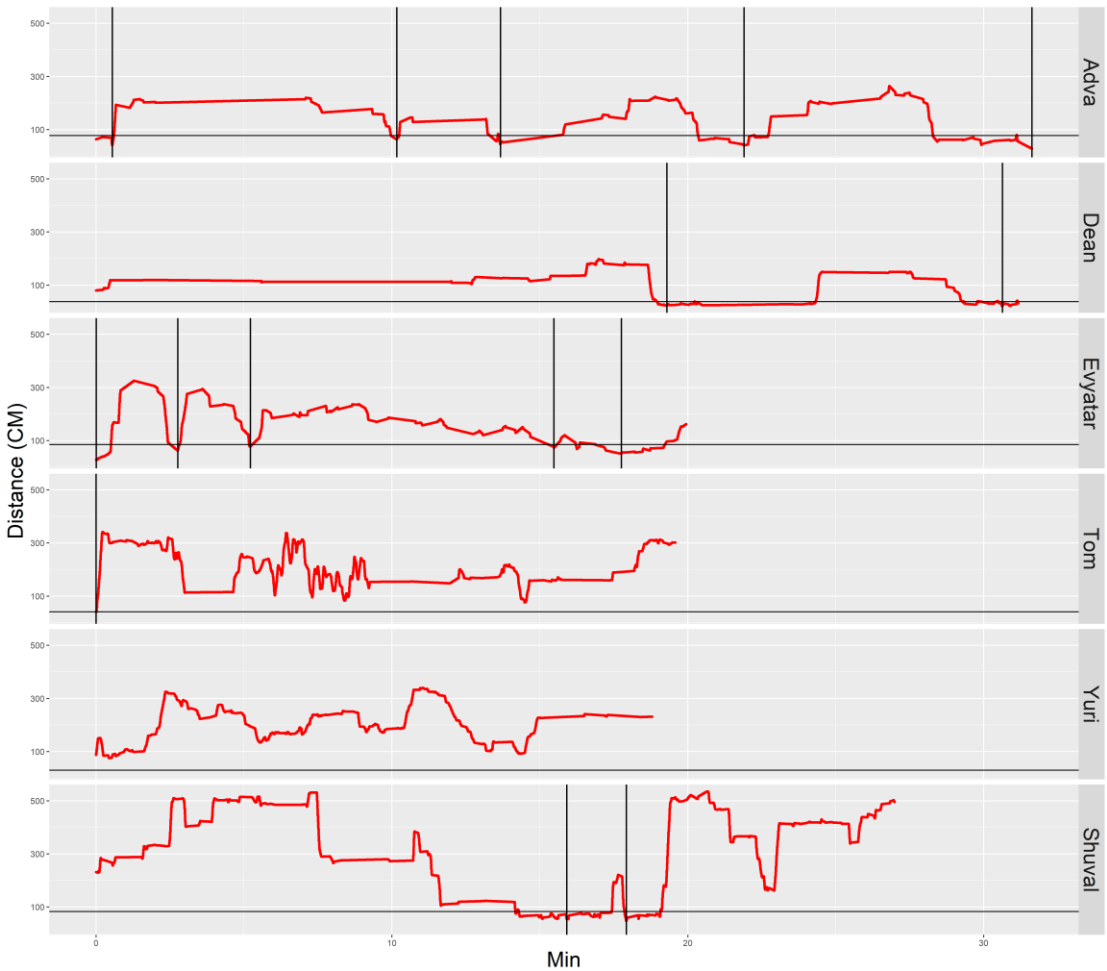

Figure 5 b. A plot of the NTD infants' management of distance from mother highlights few, if any visits to mother, shallow engagement with the mother (hardly any sections below the horizontal line) and a tendency to start the session with flat-topped peaks (long durations of staying at a specific distance, indicating long staying in place episodes). Only three of the infants end the session on mother's lap. Red line plots distance from mother, black horizontal line marks mother's customized boundary, and black vertical lines segment the plot into excursions.

The NTD plots are characterized by long straight lines that maintain a relatively fixed distance in reference to the mother's location line, indicating that these infants are slow (See *endpoints summaries* – progression speed), walking away from mother and staying away for long durations while the TDs bounce back and forth across the y-axis, being more dynamic (See *endpoints summaries* – distance normalized). It should also be noted that the maximal distance from mother is much higher in the TDs, except for Shuval whose mother is located, unlike all the other mothers, at one end of the room (see fig. 2b).

Physical contact with mother.

Although visits to mother do not necessarily imply physical contact, a major difference between the TD and NTD infants was the amount of physical contact they established with their mother (See *endpoints summaries* – contact episodes and % of contact time). All the TD infants except for Alexey ended the session with a relatively long contact episode. In the NTD group only two infants ended the session that way. The other four infants either ended the session by staying in place away from mother. It should be noted that some of the short physical contact episodes were initiated by the mothers who leaned forward and established physical contact with their nearby passing infant.

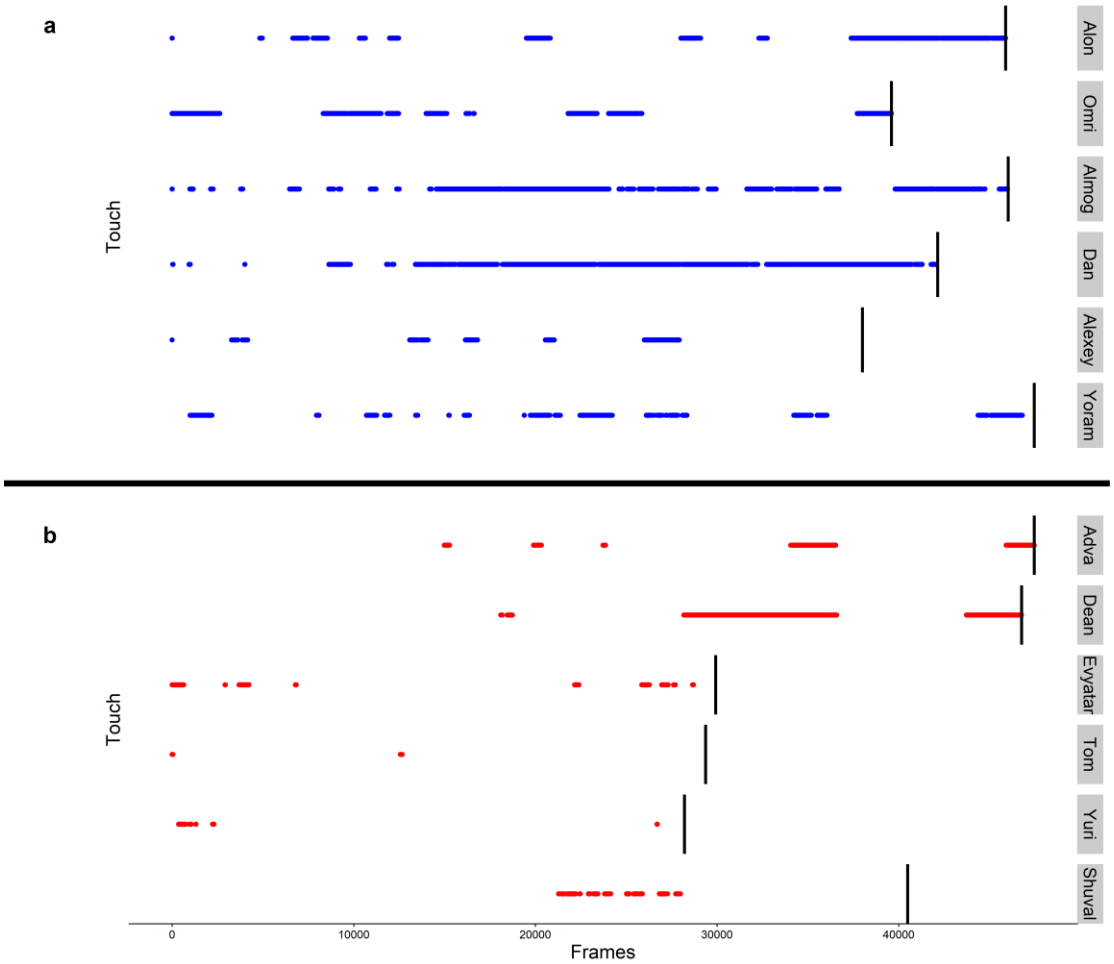

Figure 6. The duration and frequency of episodes involving physical contact with the mother were high in the TD infants and low or almost absent in the NTD infants. The vertical black lines represent the end of the respective infant's session.

Endpoint Summaries.

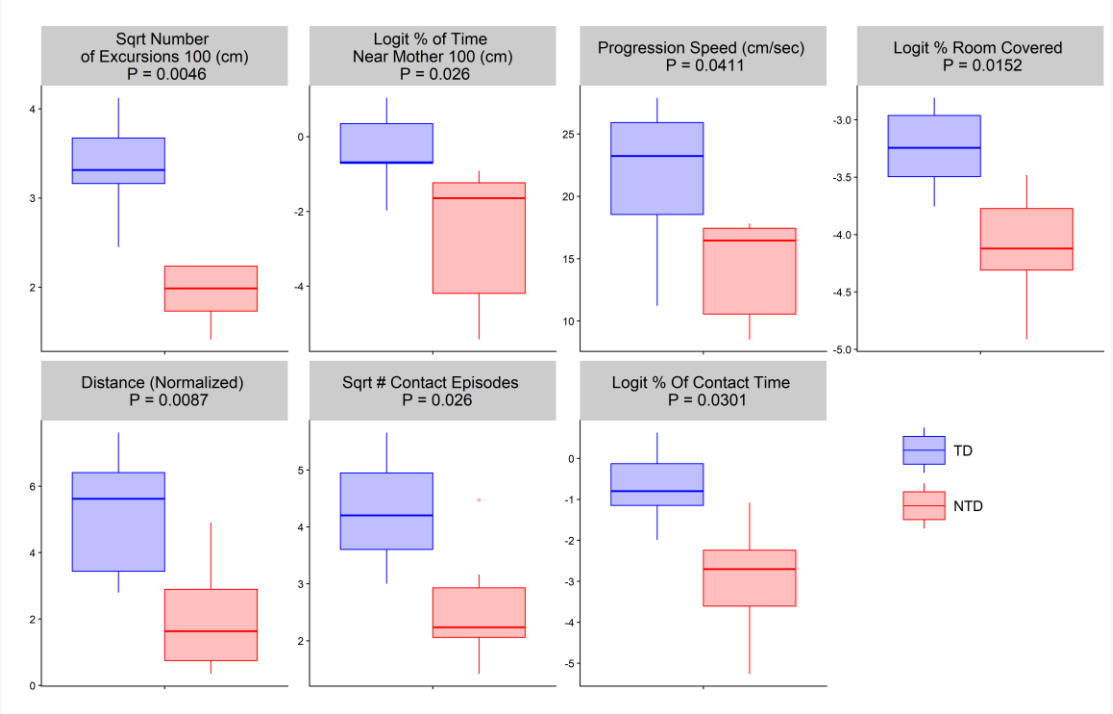

Figure 7. Box plot summaries demonstrate significant differences between the TD & NTD infants' behavioral endpoints. All comparisons were conducted using Wilcoxon rank test.

Across all endpoints the differences between the TD & NTD infants are significant (at significance level 0.05) after correction for multiple comparisons[23]. The comparison between the number of excursions and % dwell time is dependent on the radius which defines the mother's location. The difference remains robust to changes of that radius (see fig. S1 and associated text in *Supplementary Information*).

Excursions versus one un-partitioned path.

The animations presented below demonstrate the partitioning of the path into excursions in two selected TD infants.

Animation: Partitioning of Almog's path into excursions (TD infant)

Animation: Partitioning of Alon's path into excursions (TD infant)

Animations of similar partitioning of the paths of all the other TD infants are presented in the supplementary material (S videos 1-6). The TD infants exhibit a highly mother-centered organization involving excursions with clear outbound and then clear inbound portions.

The animations of the paths of two selected NTD infants, presented below illustrate how the NTD paths tend to avoid mother's place.

Animation: Partitioning of Yuri's path into excursions (NTD infant)

Animation: Partitioning of Tom's path into excursions (NTD infant)

Animations of a similar, half-hour unpartitioned paths of all the other NTD infants are presented in the supplementary material (S videos 7-12). The NTD infants tend to avoid visits to mother.

Discussion

Classical infant-mother studies: Serving psychotherapy[21], psychoanalytic theory[18], or the study of the infant's emotional life[24], currently also in correlation to neural maturation[25], most classical researchers of human infant mother-related exploration prioritize the analysis of its functional aspects. This includes, for example, the study of attachment[16,24,26], detachment[19], separation-individuation in the infant's intrapsychic life[18], sense of infant's self[21], and intersubjectivity[27,28]. As such these studies typically attend to multidimensional categorical prototypes involving expert evaluation such as secure or insecure relationships[26], as well as to key episodes disclosing emotion and attention[21]. Using the researcher's own free floating attention "the psychoanalytic eye lets itself be led wherever the actual phenomenological sequences lead"[18], disposing of spatiotemporal continuity. Whether reporting selectively or scoring in real time or from video, the classical researchers' attention is typically attracted to the mother's and infant's face and hands, describing head movement-, gaze-, facial expression episodes, crying, vocalizing, and manual manipulation of objects (e.g.,[18,21]) leaving the study of the structure of whole body movement, which carries along the head and the hands across the environment, to students of locomotion (e.g.,[29]) and exploration, who do not necessarily focus on the mother-infant interaction (e.g., [30–33]).

Current study: Complementarily, we study human infant mother-related exploration in a phylogenetic perspective, prioritizing the analysis of its structure[34], but in reference to mother. To accomplish this aim we focus on the scale of moment-by-moment (*actualgenese*; actual-genesis), using reports on close and remote taxonomic groups' origin-related behavior as background. Given our aim, a main requirement we

fulfill is representing behavior in a way that would be useful in comparisons across taxonomic groups of e.g., arthropods and mammals, including primates. The plot of the path traced by the infant fulfills this requirement; using improved tracking technology, it should, however, be enhanced in future studies with concurrent separate representation of progression, of trunk orientation, and of the relations and changes of relation between all the moving parts of the kinematic linkage[35,36] (clearly also including hands and head movement, facial expressions, gaze and vocalizations, as well as a continuous record of mother's visual attention, a most important parameter[37.] not examined in the current study). Having analyzed the infants' path in the environment we isolate what appear to be candidate natural particulate processes[38,39] that make up the path in arthropods[40] and vertebrates[7,41,42], constituting the elementary morphological characters of origin-related exploration[43]: progression segments and staying in place (lingering) episodes[11], excursions[6,11,12,44], and natural origins in reference to which the excursions are performed[36] (see *Excursions versus one un-partitioned path*). This organized structure[42] is used both in the same and in different organisms for different functions such as management of novelty[45] and of arousal[7], socialization[46] foraging[4], as well as the functions ascribed to human infants' behavior (attachment, etc.). One major side benefit of this type of representation and analysis is that it is inherently translational, presumably consisting of the same cross phyletic behavior[42].

Infant's management of attention and of perception in reference to a stationary mother: We ask the seated mother to let her infant slide down from her lap, and stay in place across the half hour session, as we obtain a continuous track of the infant's behavior at the path scale. Leaving the infants to their own devices had a profound effect on their behavior. Finding themselves in a novel, relatively pleasant environment, without being continuously bombarded by social stimuli, yet under the relatively silent visual attention of mother (only one or two of the mothers sporadically sink into reflection), the infants are entrusted with the full management, at their own pace and for an extended period of time, of their own location, distance, opposition[47,48] and contact, and extent of engagement with mother, furniture, and toys, disclosing to the observer through their behavior the endogenous constraints that shape their attention, perception, and engagement with the physical and parental environment. By mildly reducing the mother's retrieval response in a safe

environment we uncover commonalities as well as an unsuspected disparity between the TD and the NTD infants.

A computational analysis of the number of visits to the most preferred places in TD versus NTD infants: making no presumptions about mother's significance we first establish each infant's most preferred place in the environment. This place is disclosed by the peak amount of cumulative time spent in it. To ascertain that the place is indeed preferred persistently across the whole session we also require that dwell time would be incrementally accumulated in that place through a sequence of visits that would be more-or-less evenly spread across the session. Places marked by these features happen to be located in mother's proximity in five out of the six TD infants but in none of the NTD infants (figs. 2a, b). Having established the preference for mother's proximity in the TD infants we then plot in the order of performance the times of start, the duration, the time of end, and the extent of each and all of the infant entries into mother's proximity (figs. 3, 4). In addition, we calculate the number of visits to mother by establishing a customized[49] boundary for each infant-mother session (see "segmentation to excursions" in *methods* and fig. 5). Finally, we show that the TD infants pay a higher number of visits to mother at all distances regardless of where we establish a boundary (fig. S1). Most of the TDs mothers are thus visited persistently across the session, whereas most of the NTDs mothers are visited rarely and irregularly if at all (see boxplot summaries fig. 7).

Partitioning the flow into excursions. Visits to mother are next used to partition the overall path into excursions that start and end at mother's vicinity (vertical bars in fig. 5a, b). The segmentation of the path into excursions reveals that the TD infants perform a median of 12±5 excursions per session whereas the NTDs perform 3±3; three of the NTD infants do not perform any excursions at all. Furthermore, the TDs come to extensive grip with mother, not only by physically touching her during visits (fig. 6) but also by climbing and thus deeply engaging her (figs. 3,7). Some of the TD infants, like Almog, perform relatively simple excursions composed of clear, relatively monotonical outbound and monotonical inbound portions in reference to mother: their exploratory path is tightly centered on mother. Others, like Alon perform both simple and complex excursions that include several non-monotonical back-and-forth shuttles[7] on the inbound portion of the excursion. Still, all the TDs exploratory paths are tightly centered on mother.

The importance of excursions in infant-mother relationship. In TD human infants the excursions are both the units of exploration of the environment and the units of discourse with mother. They are repeated sequences of alternating interactive units of experience with mother and with the world, encompassing both the world and mother in the same excursion. Mother experience and world experience come in pairs. The excursion is a manner of interaction between the infant and his mother, a “schema-of-being-with-mother"[21], managed mostly by the infant, who "makes love" with the environment and "rushes to tell mother", much like a playing together or a sharing-of-feeding episode. It is a sequence that takes on "a regular, almost canonical form that can become an internalized model used to evaluate current experiences[21]. The "checking back pattern" is the most important fairly regular sign of beginning somato-psychic differentiation according to Mahler, who considers it to be the most important normal pattern of cognitive and emotional development. Its central role is expected considering that for most of human and primate history infants were probably carried by their mothers, using mother as an origin during forays into the environment, unlike the infants of other mammalian orders who either follow mother, or are being nested, or being cached[22].

The ontogeny of primate infant mother-related excursions: In the first postnatal period, mothers of monkeys, baboons, and chimpanzees carry their offspring continuously, until a time when the infant descends off mother, making increasingly longer excursions away and back to her[13,50,51]. In Chimpanzees, starting from the 8th month and on, the infants make short excursions remaining within arm's reach from their mothers, and then, across months, gradually increase the frequency and maximal distance of excursions to the point that the mothers might become invisible to the infant for extended durations[51]. A similar growth in the frequency and extent of excursions has been documented for a variety of monkeys kept in captivity[19,46,52–55]. Even in controversial rearing-in-isolation experiments, where the monkeys were reared in the presence of surrogate mothers made of wire, the infants used the surrogate as their "base of operations" moving away to examine furniture in the environment and then returning to base[56].

In all the mother-infant interactions in primates, both partners initiate departures and approaches, contributing to the management of distance and contact between them[46,51]. In rhesus monkeys, the relative proportion of infant initiated departures and

approaches increases with age[57]. One way infant chimpanzees manage the distance with mother is by whimpering and inducing retrieval[51]. The human mother appears to retrieve the infant during the pre-walking stage less often than many other mammals do, using environments where restraining and retrieving are less necessary. One third of the inbound trips in 10 months old human infants' excursions did not end with actual physical contact: "to see seemed sufficient[19] . Human infants, unlike many other mammals, venture to explore away from their mothers at the first moment any mode of locomotion is possible[19]; they do not wait until they can creep or walk efficiently.

The phylogenetic status of human infant mother-related exploration: The claim that mother-related exploration is homological across the primates is supported by the distinct taxonomic distribution of the carrying plus using mother as origin plus shared alternation between progression and lingering, plus excursions, all vis-à-vis the distinctly different taxonomic distribution of following, nesting, and caching[22]. The claim that this behavior is homological to origin-related exploration in fruit flies, crustaceans, rodents, and fish is supported by the shared connectivity[38,58] characterizing this behavior across phyla. The wide range of functional contexts in which the same structure unfolds is an essential characteristic of evolutionarily conserved characters: in the context of developmental evolutionary biology origin-related behavior is a character identity[38] supporting different functions. Establishing the evolutionary conserved status of human infant mother-related exploration and of its constituents would provide a ground plan guiding the search for a homeomorphic organization mediating this plan's architecture in the brain.

The paucity or absence of excursions in NTD infants is remarkable in view of the universality of mother-related exploration in primates and the sharing of origin-related behavior in vertebrates and arthropods. In the absence of a preferred stable place, the NTD infants' path could not be segmented into excursions. The NTDs path is punctuated like that of the TDs path by lingering episodes, but these episodes tend to be situated away from mother. As soon as the session starts, both TDs and NTDs slide down from mother's lap crawling away, but while the TDs tend to immediately progress back and forth in reference to mother, lingering briefly in several locations along the excursion's path, the NTDs perform an extended staying-in-place episode as soon as they reach a piece of furniture or a toy (Adva, Tom, Evyater and Shuval), or

as they stop in an empty space away from walls (Dean), tending to get stuck at that location for extended durations (fig. 5b). Such extended staying in place episodes are also performed by TD infants, but typically much later in the session, only after performing a sequence of short staying-in-place episodes (fig. 5a Alon, Almog, Dan and Yoram). The paucity or absence of visits to mother in the NTDs does not necessarily imply ignoring mother; preliminary analysis of infant gaze suggests that these infants gaze at mother from across the room at least as often as do the TD infants. The "glass wall" surrounding the NTD mothers (e.g., Tom and Yuri) appears to disclose a mixture of active avoidance of proximity including partial or full evasion of physical contact with mother (fig. 6), and an enhanced focused attention on objects.

Left to their own devices under the extended *Laissez-faire* attention of mother, the operational worlds of the NTD infants unfolded as a single, undividable, attentive yet haphazardly oriented (exhibiting no reference to an origin) slab of behavior. To our knowledge no vertebrate or arthropod has been reported so far to exhibit such behavior, nor have we been able to identify an animal model, be it a fruit fly, a rodent or a monkey, performing active investigation of the environment, without referring to an origin, or by being relatively free of the attraction of an origin. The search image portrayed by the present study for such model thus shapes up as an animal capable of switching origin-related behavior off.

The current study may intrigue us to associate the described behavior of the NTD infants with early signs of autism as these infants were referred to the Mifne Center for Early Treatment of Autism for assessment and/or treatment. However, such conclusion is beyond the capacity of this study. In order to make such an association it would be necessary to replicate[59] this study in large groups of TD and NTD infants, concurrently performing follow up developmental tests at older ages, screening for developmental disorders including Autism Spectrum Disorders (ASD).

Experimental design & methods

Six 8-12 months pre-walking infants recruited with their respective mothers to participate in a videotaped half hour session conducted at the Mifne center, and six 8-12 old Non-Typically Developing (NTD) infants who applied to Mifne center for a developmental assessment and/or treatment, following referrals by child neurologists (three infants) and expert clinicians (three infants), all documented at the stage of stable crawling, participated in this study, along with their mothers. Parents were asked to volunteer for the 30 min observation experiment after providing them with a pamphlet explaining the research. Then they were asked to sign a form designed by us and approved by the ethics committee of Tel Aviv university. The Mifne infants underwent external expert developmental assessments. The assessments included the verification of inclusion and exclusion, detailed family history, perinatal, medical and developmental history, physical and neurological checkups. On each trial the mother entered the trial room carrying her infant, sat on a mattress in the periphery of the room and then seated the infant next to her. The mother has been requested to remain seated within the area of the mattress and allow the infant to act freely for a 30 minutes session. Not all sessions lasted for half an hour, some being stopped whenever there seemed to be an inconvenience to the infant (see figs. 5, 6). 2 video cameras, one obtaining a static view of the whole room including the infant and the mother (fig. 1), and another zooming on the infant and following him were used across the session. The behavior of the infant and the mother was videotaped for half an hour, a period found to be appropriate in our preliminary study. The static camera data were transformed to a top view (see below). Data were prepared for segmentation[11,41,60] and were subjected to analysis by SEE, a publicly available Software for the Exploration of Exploration developed and elaborated by us for many years (www.tau.ac.il/~ilan99/see/)[11] .

*Room***:** The infants were tracked in a medium-sized, 3.65m by 5.45m room. The mother was asked to stay seated on a pillow for the whole session.

Tracking: The tracking of the infant was done manually by using a specifically made program in Matlab. The infant's location was tracked every ~15 frames; missing coordinates were filled using linear interpolation.

We resorted to the use of manual tracking after exhausting other possibilities, different tracking algorithms failed due to bad image quality, multiple object moving

and the fact that the infant is a large object, so even when tracking was successful, there was jitter across the child body.

Transformation: The room was videotaped from a high side view camera angle requiring a projective transformation to an exact overhead view that would replace the 2D coordinates in the video image (fig. 1, left) to 2D coordinates in the world (fig. 1, right). A projective transformation is an image processing technique finding the linear transformation from one coordinates basis to another. It was implemented in Matlab, by choosing 4-5 points (which coordinates were known for both bases) and solving for the projection matrix.

Cumulative dwell time maps (heatmaps): The construction of the heat maps involved several steps:

1. Obtaining the original coordinate data from the Matlab tracking.
2. Smoothing the coordinates using the SEE program (https://www.tau.ac.il/~ilan99/see/).
3. Dividing the room into a grid, where each cell is a $1\ (CM) * 1\ (CM)$, and calculating the time spent in each cell according to 2.
4. Smoothing the cells using a 2d Gaussian smoother: calculating for each cell a new value according to the weighted average of the cell itself and its neighboring cells. The weights are given by the a 2d Gaussian distribution ($\sigma^2 = 14, n = 63$) (fig. 8)

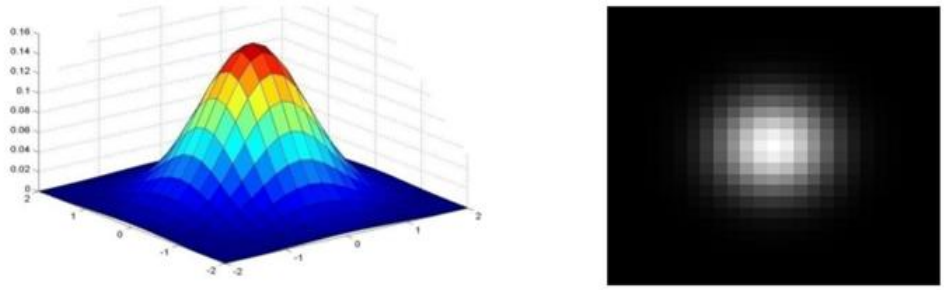

Figure 8. A visualization of the weights generated by a 2d Gaussian distribution

5. Finding local maxima of the smoothed coordinates and discarding the 96% of maxima's with lower values.
6. Calculating the number of visits to each local maximum, based upon the two concentric circles ($r_{in} = 30, r_{out} = 50$) paradigm described below.

We used several distinct ways for visualizing and scoring the infants' visits to places and for segmenting the path traced by them across the session. We calculated the number of visits to peak dwell time places across the room using the two concentric circles algorithm; we used engagement plots to visualize all the infant's entries into mother's close proximity, including their extent and duration; and we established a customized boundary for each mother's place in order to calculate the number of visits paid to mother and the number of excursions or roundtrips performed from her into the environment.

Using two concentric circles to calculate the number of visits to a place: The number of visits to a circumscribed area could be calculated by selecting a location, tracing a radius around it, and counting the number of times the infant entered the defined circular area. However, small vacillations of the infant across the border of the circular area without actually crawling away and returning would count as distinct, multiple visits. To avoid this outcome, we define two concentric circles, both centered around the same location of interest. A visit starts when the infant enters the inner (r_{in}) circle and ends when he exits the outer circle (r_{out}).

Engagement Plots: The engagement plot exhibits the timing, duration, and extent of the infant's being in gear with mother and with furniture and doors in the room. Each set of concentric circles exhibits the behavior of a specific infant. Starting at twelve o'clock and proceeding clockwise for the session's duration, the arc traced on the circle's circumference and the colored section of the circle, designate the time of start, the time of end, the duration in session percentage, and the extent of the entry into mother's or any other large object's close proximity (the infant seemingly casts a shadow on the peripheral area separated from the circle by its entry). The color of the polygon stands for the visited object, mother being colored in red. . Furniture are designated by specific colors. For radius R, time t and for object j a point is drawn according to $I\left(D_{j,t} < R\right)$, $D_{j,t}$ being the distance of the infant at time t from the center of object j. In order to compare multiple pieces of furniture with different sizes, the distance drawn on the plot are the distance of the infant from the object minus the radius of the object. See figure S2.

Segmentation to excursions: To partition the infant's path across the session into excursions we had to define for each mother the customized circumscribed place she

occupied. The length of the radius tracing the boundary of mother's place in reference to mother's center influences the number of visits paid by the infant to mother across the session: the smaller the radius the fewer the number of visits. To obtain a customized place around the location defining mother's center, we progressively increase the radius circumscribing mother's location, dynamically changing the number of visits paid to mother. The minimal radius yielding a relatively stable number of visits for a vector of protracted lengths of radii is selected as the radius defining mother's place. We obtain the number of visits by using the two concentric circles method for each inner circle radius between 30 cm to 120 cm and an outer circle radius that is larger by 1.1 then the inner circle radius, then search for the longest radii interval in which there is no change in the number of visit, and then choose the smallest radius of that interval.

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Supplementary Information

Quantitative examination of dwell time distribution in reference to mother.

To quantify dwell time, we plot the average time spent across the session for the whole range of distances from mother's center to a distance of up to 1.5m shows that the TD infants spend significantly more time than the NTD infants for the whole range marking mother's vicinity. Only the apparently TD infant Alexey (see *methods*) shows the lower values characterizing the NTD infants. The lowest curve for both number of visits and dwell time in the TD infants belongs to the exceptional Alexey. Using permutations test the difference between the two curves is significant (p-value 0.026, the average difference between the curves is 0.19).

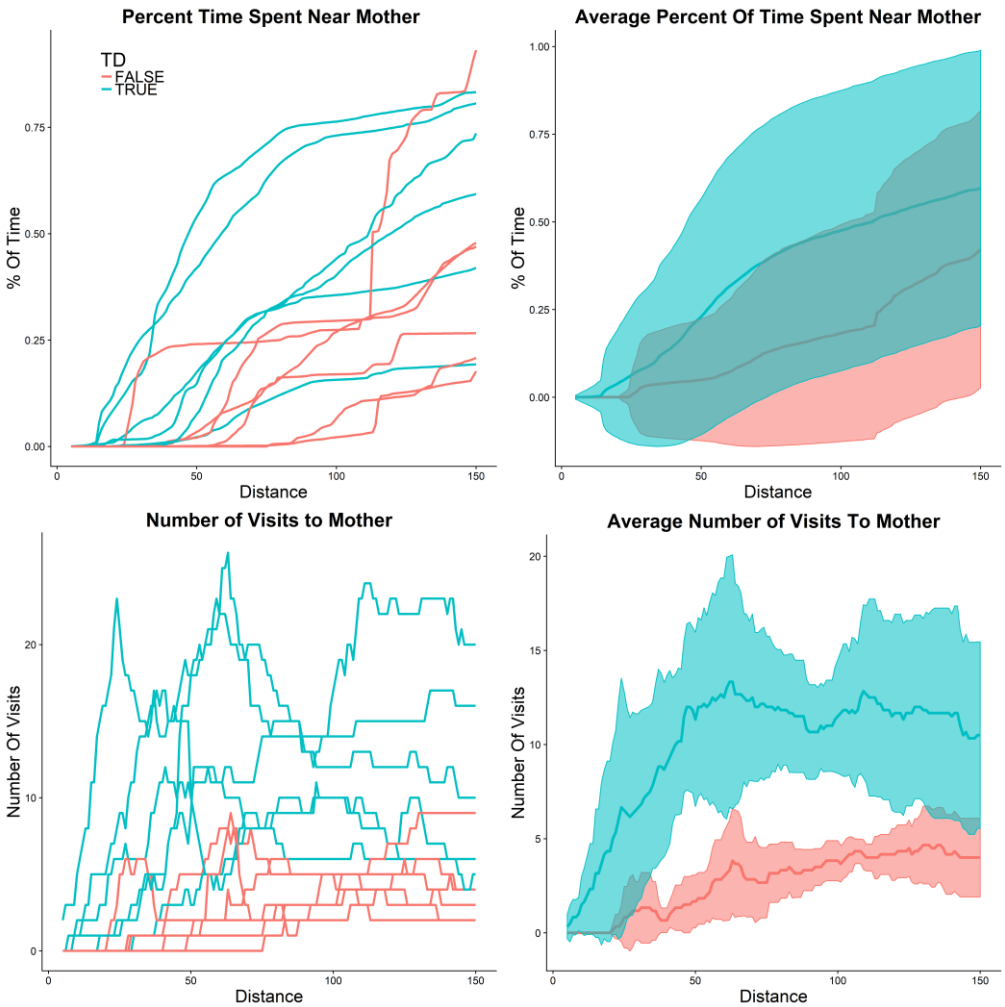

Figure S1 a, b, c, d. Percent of time spent in mother's vicinity. **c, d**: Number of visits to mother as a function of distance from mother. The CI for figures **b** and **d** is obtained using the normal approximation.

Quantitative summary of number of visits-to-places distribution in reference to mother.

Plotting the number of visits paid by each of the infants to the mother as we dynamically change the inner radius of the two circles algorithm (the outer radius is kept at 1.1 of the inner radius) shows that the number of visits to mother are higher for the TD compared to the NTD infants for the whole range of radii up to 1.5m. Since excursions are punctuated by visits to mother (see section *The infants' management of distance from mother*), it also follows that for all considered distances from mother the TD infants exhibit more excursions than the NTD infants. Using permutations testing the difference in excursions between the TD and NTD is highly significant (p-value - 0.0006, the average difference between the curves is 7.23 visits).

Engagement Plots.

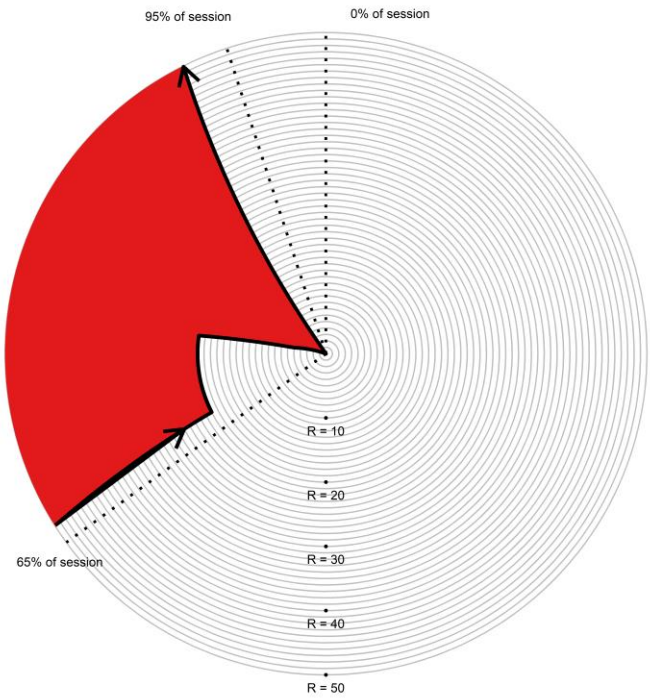

Figure S2. Illustration of an interaction plot including annotation. The red wedge represents the % of time the child spent near mother, the concentric circles radii represent the distance of the infant from mother and the length of the arc at the respective radius represents the % of time spent at that distance (or higher).

Videos.

Animations of the infants sessions were created and can be view using the following links. Notice that the infant sometimes appear out of the bounds of the room, this is due to tracking the child and then transforming the image, so when the infant is standing it appears that the tracker is out of bounds. The mother size is changing between video to video, this is due to the way each mother sat (some were almost lying down).

The baby center of mass in the current frame is represented by a black circle, movement in the current excursion is segmented to lingering segments and progression segments represent by blue, and red colors respectively, past excursions are shown in grey. The mother location is green while the rest of the furniture is black.

TD infants.

Video S1 – Alon animation of excursions

Video S2 – Omri animation of excursions

Video S3 – Almog animation of excursions

Video S4 – Dan animation of excursions

Video S5 – Alexey animation of excursions

Videos S6 – Yoram animation of excursions

NTD infants.

Video S7 – Adva animation of excursions

Video S8 – Dean animation of excursions

Video S9 – Evyatar animation of excursions

Video S10 – Tom animation of excursions

Video S11 – Yuri animation of excursions

Video S12 – Shuval animation of excursions