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Age-related changes in the organization of spontaneously occurring behaviors

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ABSTRACT

Age-related changes in spatial and temporal processing have been documented across a range of species. Rodent studies typically investigate differences in performance between adult and senescent animals; however, progressive loss of neurons in the hippocampus and cortex has been observed to occur as early as after adolescence. Therefore, the current study evaluated the effects of age in three- and ten-month-old female rats on the organization of movement in open field and food protection behaviors, two tasks that have previously dissociated hippocampal and cortical pathology. Age-related differences were observed in general measures of locomotion, spatial orientation, and attentional processing. The results of the current study are consistent with age-related changes in the processing of spatial information and motivation that occur earlier in life than previously anticipated. These observations establish a foundation for future studies evaluating interventions that influence these age-related differences in performance.

1. Introduction

Age-related changes in performance on cognitive tasks are influenced by a variety of factors. For example, the nature of the information processed in the cognitive task influences the trajectory of age-related change. Specifically, from age 20–70 years, humans exhibit a slight increased performance on vocabulary knowledge tasks; whereas performance on spatial and memory tasks deceased over the same time frame (Salthouse, 2009, 2010). The neural systems that support performance on these tasks may be differentially sensitive to the effects of age. Online processing of spatial and temporal information is dependent on a network of brain structures that are sensitive to the effects of age. The hippocampal formation is one component of this network which has been observed to exhibit structural changes when rodents reach 18–24 months of age (Kuhn et al., 1996; Seki and Arai, 1995). However, there is evidence that these structural changes may occur at earlier developmental time points (Calabrese et al., 2013; Driscoll et al., 2005, 2006). For example, from 4-11 months of age, the rodent hippocampus exhibits a significant reduction in proliferation of new neurons (Nada et al.,

2010), an increase in neuronal loss (Morterá and Herculano-Houzel, 2012), and a decrease in synaptic density (Saito et al., 1994). In contrast, rats within this age range typically do not exhibit age-related changes in performance on the Morris water task (Frick et al., 1995). This observation may reflect the limitations of the Morris water task to detect subtle age-related changes in hippocampal function (Baxter and Gallagher, 1996; Cain et al., 1996; Whishaw and Tomie, 1997).

Traditional assessments of spatial memory have failed to dissociate the source of information an animal used to maintain spatial orientation. For example, environmental cues (e.g., visual, auditory, olfactory stimuli) support a piloting-based navigational strategy, such as observed during place learning in the Morris water task. However, when environmental cues are unfamiliar or unavailable, many animal species can use self-movement cues (e.g., proprioception, vestibular cues, optic flow) to guide movement (Barlow, 1964; Gallistel, 1990; Maaswinkel and Whishaw, 1999; Mittelstaedt and Mittelstaedt, 1982). Previous work has demonstrated that the rodent's ability to use environmental cues are spared with selective hippocampal pathology (Baxter and Gallagher, 1996; Dornan et al., 1996; Frielingsdorf et al., 2006; Jonasson

et al., 2004), whereas studies that dissociate environmental and self-movement cue use have provided evidence that the hippocampus supports the processing of self-movement cues in rodents (Martin and Wallace, 2007; Whishaw et al., 2001; Winter et al., 2013). Tasks that dissociate processing of different sources of information may be more sensitive to detecting age-related changes in performance.

Spontaneous behaviors (e.g., open field, food protection) consist of highly organized sequences of movement. This movement organization is dependent on the ability to process ongoing spatial and temporal information. For example, rodents exposed to a novel environment will establish a home base and maintain a representation of current position in the environment relative to this point. This online representation can be used to estimate direction and distance to the home base. Under light or dark conditions, rodents organize their movements into sequences of non-circuitous progressions punctuated by stops in which most change in heading occurs (Donaldson et al., 2019; Eilam and Golani, 1989; Osterlund Oltmanns et al., 2021; Wallace et al., 2006b; Whishaw et al., 2001). Stops tend to be focused on the periphery of the apparatus and clustered in one position, with environmental cues influencing the direction of clustering (Hines and Whishaw, 2005). Pathology specific to sources of self-movement cues, such as the vestibular system, disrupts this organization. Rodents with vestibular pathology exhibit circuitous progressions, large changes in heading, and often establish less stable home bases (Banovetz et al., 2021; Blankenship et al., 2017b; Donaldson et al., 2018). These disruptions in movement parallel the spiraling movement exhibited by disoriented humans (Schaeffer, 1928; Souman et al., 2009). Both the vestibular system (for a review, see (Smith et al., 2019)) and hippocampus, systems critical for self-movement cue processing, are susceptible to the effects of aging. Therefore, evaluating the organization of movement during open field behavior under dark conditions may be sensitive in detecting early age-related changes in hippocampal-dependent spatial processing.

Protecting a food item from an approaching conspecific represents another highly organized spontaneous behavior that depends on spatial and temporal processing to guide movement. For example, successfully protecting a food item depends on the ability to attend to the direction of the approaching conspecific, and the ability to estimate the time required to consume the food item (Whishaw and Gorny, 1994). Specifically, if the rat is approached while estimating a longer consumption time, then it will elicit a large lateral movement that depends on transferring the food item to the mouth and using forelimbs to assist locomotion (dodge). In contrast, if the rat is approached while estimating a shorter consumption time, then a smaller lateral movement will be elicited in which the forelimbs maintain contact with the food item (brace). While consuming a food item, rats will switch between an early phase when dodging behaviors are more likely to occur and a late phase when bracing behaviors are more likely to occur. This spontaneous organization has been used in rodents to dissociate the neural contributions to spatial and temporal processing (Martin et al., 2008; Wallace et al., 2006c; Whishaw and Tomie, 1987, 1988). Cholinergic deafferentation of the nucleus basalis (Martin et al., 2008) or N-methyl-D-aspartate (NMDA) lesions focused on the dorsocentral striatum (Blankenship et al., 2017a) in rodents disrupted the ability to protect the food item from theft; however, when a food item was successfully protected, rodents exhibited a spared ability to switch from dodges to braces. In contrast, cholinergic deafferentation of the hippocampus spared the ability for rodents to protect the food item, but disrupted the ability to switch from dodging to bracing (Martin et al., 2008). This suggests that while cortical regions support attentional processing of environmental cues, the hippocampal cholinergic system supports processing of spatial and temporal cues. Therefore, observing age-related differences in the organization of food protection behaviors may reflect age-related changes in hippocampal and/or cortical function.

The organization of spontaneous behaviors have provided robust tools to investigate the neurobiological basis of spatial and temporal processing. Biological changes in the brain have been well documented throughout development across both humans and rodents (Bagarinao et al., 2019; Daniel, 2013; Kuhn et al., 1996; Seki and Arai, 1995) with changes in hippocampal neuroplasticity even observed in mid-adulthood (Daniel, 2013; Driscoll et al., 2005; Nada et al., 2010; Rodgers et al., 2010). However, these early changes have not been evaluated in the context of spatial and temporal processing using the spontaneous organization of open field and food protection behaviors. Therefore, the current study evaluated the organization of movement in the open field under completely dark conditions and food protection behavior in three-month and ten-month old rats. The topographic and kinematic movement organization of these behaviors provided a basis to characterize age-related changes in spatial orientation, motivational, attentional, and temporal processing in female rats.

2. Materials and methods

2.1. Animals

Three-month-old female (n = 7) and ten-month-old female (n = 7) Long Evans rats were obtained from the Northern Illinois University vivarium for the open field task. Three more rats were added to the set of ten-month-old female rats (n = 10) that were subsequently tested in the food protection task. Their performance was evaluated relative to a different set of three-month-old female rats (n = 12). Long-term adlib access to food has been associated with multiple health concerns in rodents (Yu et al., 2002). Therefore, rats assigned to the ten-month-old group were weight-maintained beginning at three months of age. Specifically, individual weights were obtained on post-natal days 90, 91, and 92. Each rat's average weight across the three days was used as their daily goal weight (+/- 2 %) and determined the amount of food that was provided daily. To elicit food motivated behavior, both age groups were exposed to a gradual food deprivation procedure that reduced each rat to 85 % of their average weight obtained from post-natal days 90, 91, 92 two-weeks prior to behavioral testing. All rats were maintain at this level of food deprivation for the duration of behavioral testing. Rats were pair housed in opaque plastic cages in a colony room maintained on a 12 h light/dark cycle in a consistent temperature (20– 21 °C) and humidity (40–60 %) controlled climate. All experimental procedures were approved by the Northern Illinois University's Institutional Animal Care and Use Committee which follows standards set by the Office of Laboratory Animal Welfare.

2.2. Apparatus

The open field was a wooden circular table (198 cm in diameter, 130 cm above the floor) painted white and located in a room under completely dark conditions. A night vision camera was attached to the ceiling and provided a view of the surface of the table. Open field sessions were recorded on DVDs at 30 frames per second for offline analysis using Noldus Ethovision XT 13 animal tracking software. Four infrared emitter banks illuminated the room with infrared wavelength to make the session visible on the night vision camera. Infrared is a wavelength that rats are unable to visually detect (Neitz and Jacobs, 1986). Night vision binoculars were used to place the rat on the center of the table and remove the rat after the conclusion of the experiment.

The food protection apparatus was a Plexiglass cylinder (17 cm in diameter, 30 cm in height) that was located on a transparent table. LED lights illuminated the cylinder from underneath. Behavior was recorded from below using an angled mirror and a high-definition video camera positioned perpendicular to the mirror (Blankenship et al., 2017a; Martin et al., 2008; Peters, 2018; Pinel et al., 1992). Videos were filmed at 30 frames per second and were stored on DVDs for offline analysis.

2.3. Procedure

2.3.1. Open field

The open field session was filmed under complete dark conditions and occurred during the light portion of the rat's light/dark cycle. Rats were removed from the colony room and transported in a covered opaque cage following a random circuitous path into the testing room. The random circuitous path was taken to limit the rat from using the spatial relationship between the colony and testing room. The rat was removed from the cage and was placed on the center of the open field. Each rat was left in the open field for 40 minutes. Upon completion of the open field session, the experimenter placed the rat back in the towel covered opaque transport cage and followed a random circuitous path before returning the rat to the colony room. The open field was cleaned between sessions with an ammonia-based cleaning solution to eliminate odor cues.

2.3.2. Food protection

Rats were habituated to a one-gram banana flavored food pellet (BioServ) in their home cage. For the next four days, rats were trained to retrieve the banana pellet from metal tongs in their home cage. Following successful training of pellet retrieval from the tongs, rats were habituated to the apparatus. Rats were individually placed into the apparatus and given three pellets from the tongs for three consecutive days.

Following habituation, testing began which consisted of three trials for four consecutive days. The first two trials consisted of placing the dodger (rat receiving the food), with a young female conspecific in the food protection apparatus. The dodger was given the pellet with the tongs. If the conspecific stole the pellet from the dodger, the conspecific was removed from the apparatus, the stolen food was retrieved, the conspecific was placed back in the apparatus, and the food item was returned to the dodger. Thefts between female rats generally are non-aggressive and rats typically move away from each other immediately after the theft. During the third trial, the conspecific was removed from the apparatus and the dodger receive a pellet solo.

2.4. Behavioral analysis

2.4.1. Open field

Two minutes after the rat was placed on the open field, 20 minutes of open field behavior were captured for analysis. The two minute delay was based on previous work demonstrating that rodents exhibit markers of home base establishment (e.g., circling, grooming, rearing) within two minutes of exposure to a novel environment (Banovetz et al., 2021; Blankenship et al., 2017b; Donaldson et al., 2019, 2018; Osterlund Oltmanns et al., 2021). Noldus Ethovision XT 13 was used to digitize the rat's body position in the open field at five frames per second. The resulting x- and y- coordinates were used to calculate moment-to-moment speeds. The 20 minute session was divided into four samples of five minutes. A rat's average speed for the open field session was used to segment movement into progressions and stops. Progressions were defined as periods of movement greater than the rat's average peak speed for at least two captured frames, whereas stops were defined as periods of movement below the rat's average speed for at least two captured frames. Multiple measures were used to quantify general characteristics of movement, stop clustering behavior, and progression topography as described in the following paragraphs.

A variety of factors (e.g., emotion, hyperactivity) have been observed to influence general open field behavior (Denenberg, 1969; Eilam and Golani, 1990). To assess general features of open field behavior, total distance traveled, average peak speed, and total stop time were calculated from the progressions and stops. Total distance traveled was calculated by summing all progression distances across the four samples. Average peak speed was calculated by averaging progression peak speeds across the four samples. Total stop time was calculated by summing all stop times across the four samples. These measures describe general locomotion in the open field.

Rodents organize stopping behavior around a discrete location in the environment termed the home base (Eilam and Golani, 1989; Golani et al., 1993). To assess topographic features of stopping behavior, between sample stop clustering and average change in heading were calculated. Circular statistics (Batschelet, 1981) was used to quantify stop clustering. Each second of a stop was recorded as an individual observation on a cartesian (x- and y-) coordinate system. These observations were then converted to a polar coordinate system (theta and r) relative to the center of the table as the origin. Transforming to a 360° polar coordinate system with one-degree intervals allowed an analysis of the direction of the stopping behavior relative to the center of the open field. Parameter of concentration provided an index of stop clustering density with values that ranged from zero (all stops uniformly distribution around the perimeter) to one (all stops are fall within the same polar direction). The Rayleigh test was used to evaluate the uniformity of between sample stop clustering values. The Rayleigh test evaluates departure of uniformity; therefore, non-departure indicates an established home base. Finally, the percentage of stops on the periphery was calculated by taking the distance of each stop from the center of the table. The periphery of the table was defined as the outer 10 % from the average maximum stop nearest the edge of the table.

Most changes in heading in the open field occur during stops. The change in heading was calculated as the supplementary angle subtended by the progression peak speed location prior to the stop, the average stop location, and the subsequent progression peak speed location. Change in heading values range from zero degrees (no change in heading direction) to 180 degrees (complete reverse of heading direction). All changes in headings between stops were averaged across samples.

Previous work has demonstrated that rodents organize their progressions into three modes of motion, or "gears" (Drai et al., 2000; Drai and Golani, 2001). To assess topographic and kinematic features of progression behavior, each set of progressions were averaged and evenly divided into three classes of length (long, medium, short). Progressions less than 20 cm were not included in this analysis in order to exclude smaller movements associated with grooming or rearing behaviors that do not reflect locomotion through the environment. Average peak speed was calculated by averaging progression peak speeds across the four samples. Path circuity was calculated by dividing the Euclidean (shortest) distance by the actual distance traveled on the progression. Values range from zero (circuitous path) to one (direct path).

2.4.2. Food protection

Several measures were used to quantify the organization of food protection behavior. First, time to eat the food item was recorded during all food protection trials. Next, all thefts and food protection behaviors were counted during each trial. Each food protection behavior was classified as a dodge (transferring food item from the forelimbs to the mouth) or brace (pivot without transferring food item to the mouth). The timepoint in which each food protection behavior occurred during a trial was recorded and separated into early and late bins. Finally, the distance between the nose of the dodger and nose of conspecific was recorded at the initiation of a food protection behavior. The Tracker motion capture software (Open Source Physics https://phys1ets.org /tracker/) was used to manually digitize the noses of the dodger and conspecific at the start of the food protection behavior. The resulting x- and y- coordinates were used to calculate the distance between the noses. Two dodges and braces that were selected for analysis each test day were averaged separately across the four test days.

2.5. Statistical analysis

Independent samples t-tests were used to evaluate differences between ten- and three-month-old rat open field behavior with an alpha set at 0.050 and Cohen's d reported as a measure of effect size. Mixed-

designs Analysis of Variances (ANOVAs) were used to evaluate main effects and interactions for between subject (age) and within subject variables (class length) with an alpha set at 0.05. Additionally, separate mixed-designs ANOVAs were used to evaluate the between-subjects variable of age and the within-subject variables (timepoint/behavior) for percent dodges and average nose distance between the dodger and approaching conspecific. Independent sample t-tests were used to assess average eat time, total thefts, and total behaviors. The Greenhouse-

Geisser correction was used in analyses in which the Mauchly's test indicated significant departure from the assumption of sphericity. Partial eta squared (η_p^2) values were reported for each main effect and interaction as a measure of effect size. All statistical analyses used JASP 14.1 (University of Amsterdam) to calculate statistical results.
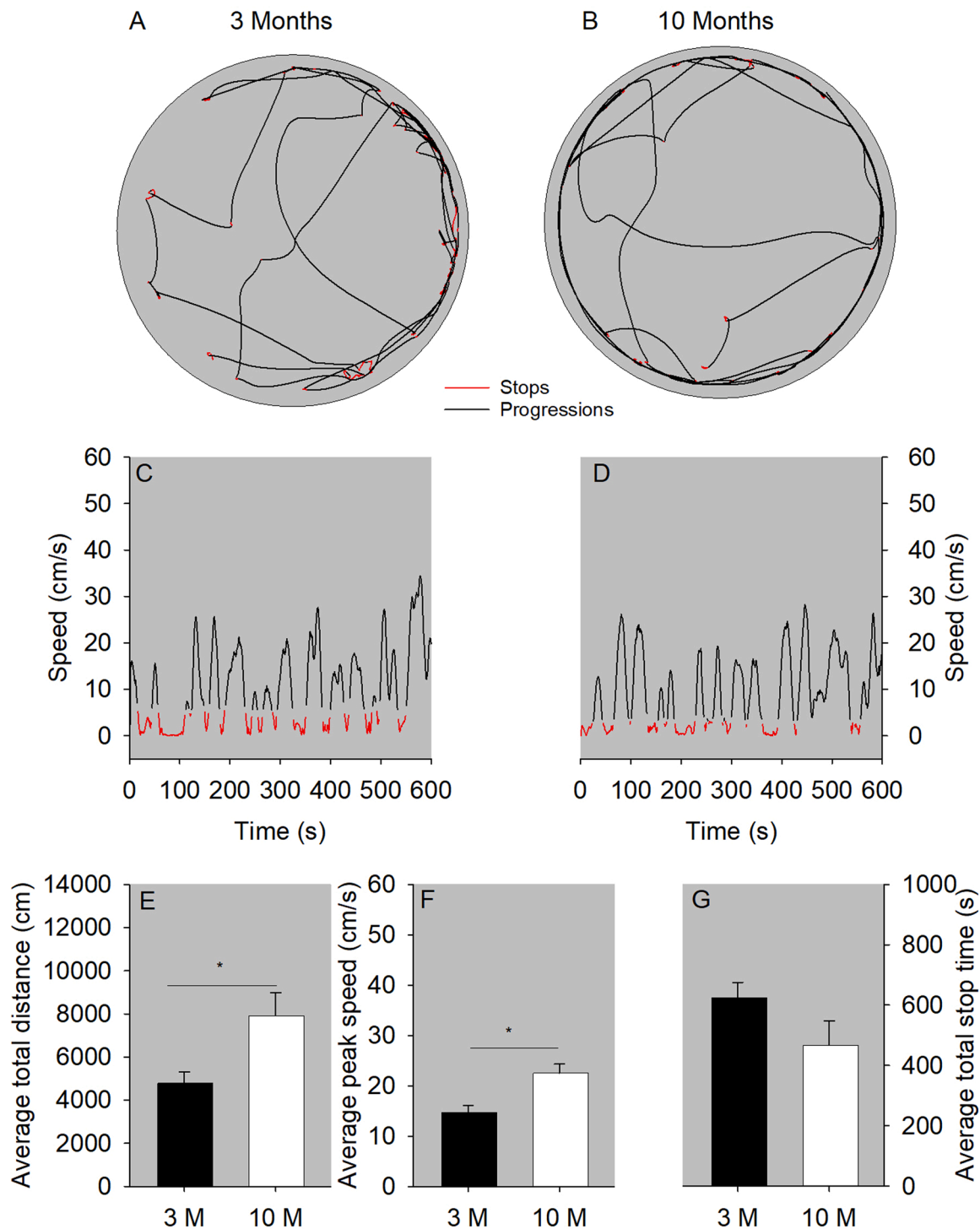

Fig. 1. Topographic profiles of progressions (black) and stops (red) are plotted for a representative three-month-old (A) and ten-month-old (B) rat for a 10-minute sample. Moment-to-moment speeds are plotted for a representative three-month-old (C) and ten-month-old (D) rat. Three-month-old rats traveled a significantly shorter distance (E) and exhibited slower average peak speeds (F), but there were no group differences in stop time (G) compared to ten-month-old rats across samples. *p < 0.050.

3. Results

3.1. Open field

All rats alternated between progressions and stops throughout the open field session (Fig. 1A–D). Independent samples t-tests were conducted to evaluate group differences on general movement (see Table 1). There was a significant effect of group on total distance traveled. Three-month-old rats (M: 4781.50 cm, SEM: 516.60) traveled a shorter distance compared to ten-month-old rats (M: 7914.50 cm, SEM: 1076.20) (Fig. 1E). There was a significant effect of group on average peak speed. Three-month-old rats (M: 14.70 cm/s, SEM: 1.30) exhibited lower average peak speeds compared to ten-month-old rats (M: 22.50 cm/s, SEM: 1.80) (Fig. 1F). There was no significant effect of group on total stop time. Three-month-old rats (M: 624.40 s, SEM: 50.30) did not have a significantly different total stop time compared to ten-month-old rats (M: 466.80 s, M: 80.60) (Fig. 1G). These findings are consistent with three-month-old rats exhibiting characteristics of lower general activity levels in the open field compared to ten-month-old rats.

All rats exhibited stopping behavior that was directionally clustered (Fig. 2A). Independent samples t-tests were conducted to evaluate group differences on stop measures (see Table 1). There was no significant effect of group for between sample stop concentration (Fig. 2B). Three-month-old rats (M: 0.64, SEM: 0.10) did not exhibit significantly different between sample stop concentration values compared to ten-month-old rats (M: 0.59, SEM: 0.10). This suggests that both groups were equally stable in stop clustering throughout the open field session. The Rayleigh test revealed that both groups generally established consistent home bases. There was no significant group difference in percentage of time spent on the periphery (Fig. 2C). Three-month-old rats (M: 93.6 %, SEM: 1.91) did not spend a significantly greater percentage of time on the periphery of the open field compared to ten-month-old rats (M: 86.2 %, SEM: 5.6).

Most changes in heading occur between progressions (Fig. 3A [open circle indicates starting position, black lines indicate progression path, black circles indicate location of peak speed, red dots indicate position of change in heading]). There was a significant effect of group for the degree of change in heading between stops. Three-month-old rats (M: 63.10 deg, SEM: 4.10) made smaller changes in heading compared to ten-month-old rats (M: 82.10 deg, SEM: 7) (Fig. 3B). To further investigate the nature of group difference in change in heading, histograms were generated for the three-month-old (Fig. 3C) and ten-month-old (Fig. 3D) rats. It appears that the ten-month-old rats exhibited more intermediated (60–120°) changes in heading relative to the three-month-old rats. This observation was supported by kernel density estimation curves generated for each rat (lines plots). Each rat's set of change in headings were sorted and equally split into small, medium, and large classes. The average change in heading is plotted for each group across the three classes (Fig. 3E). A repeated measures ANOVA conducted on change in heading revealed a significant effect of age, size, and age by size interaction (Table 2). Post hoc analyses revealed that significant group differences were specific to the medium sized change in heading. Specifically, three-month-old rats (M: 47.87 deg, 95 % CI [29.6, 66.1]) had significantly lower changes in heading relative to the ten-month-old rats (M:76.37 deg, 95 %CI [58.1, 94.6]). This pattern of

results is consistent with ten-month-old rats exhibiting more intermediate change of heading angles, relative to the three-month-old rats.

Repeated measures ANOVAs were used to evaluate main effects of progression measures, length (gear), age, and respective interactions (see Table 2). Both groups decreased average peak speeds as progression length class shortened, with three-month-old rats maintaining lower peak speeds (M: 19.81 cm/s, 95 % CI [17.22, 22.39]) compared to ten-month-old rats (M: 26.19 cm/s, 95 % CI [23.61, 28.78]) (Fig. 4A and C). On average, both groups had relatively non-circuitous progressions throughout open field behavior; however, differences emerged dependent on the length class of the progression (Fig. 4B). There was a significant effect of length on path circuity with movement becoming more circuitous in longer progression lengths for both groups (short M: 0.99, 95 % CI [0.94, 1.03]; medium M: 0.96, 95 % CI [0.91, 1.0]; long M: 0.83, 95 % CI [0.78, 0.88]) (Fig. 4D). Additionally, there was a significant length by group interaction. While both groups exhibited similar path circuity when traveling short and medium progressions, three-month-old rats (M: 0.90, SD: 0.04) exhibited less path circuity when traveling long progressions compared to ten-month-old rats (M: 0.80, SD: 0.20).

3.2. Food protection

Motivation to consume was evaluated through the average amount of time to eat the pellet with (Fig. 5A) and without (Fig. 5B) a conspecific present. When the conspecific was present, there was a significant effect of age with the ten-month-old rats eating faster (M = 48.50 s, SD = 5.80) than the three-month-old rats (M = 80.10 s, SD = 12.20). Similarly, the ten-month-old rats ate the pellet faster (M = 49.50 s, SD = 8.00) than the three-month-old rats (M = 84.90 s, SD = 15.50) when there was not a conspecific present. The total number of food protection behaviors was used to assess social interaction and engagement of dodgers and conspecifics. There were observed differences in total number of behaviors (Fig. 5C) between age [t (20) = −5.04, p < 0.001, Cohen's d = −2.157]. Specifically, the ten-month-old rats (M = 73.90, SD = 7.30) exhibited more food protection behaviors compared to the three-month-old rats (M = 47.10, SD = 13.40). The total number thefts (Fig. 5D) were used to quantify successful protection. There were no age differences for total amount of thefts [t (20) = 0.690, p = 0.15, Cohen's d = 0.30]. In general, the ten-month-old rats were observed to be more motivated to consume the pellet and more inclined to interact with the conspecific compared to the three-month-old rats.

Since there were observed differences in total food protection behaviors, the percent of dodges were calculated at both early and late timepoints within the trial (Fig. 6). Fig. 6 displays a representative dodge (A) with the dodger (unmarked belly) transferring the pellet from their forelimbs to their mouth while executing a full body turn, resulting in their forelimbs touching the floor. Additionally, a representative brace is depicted (B) with the conspecific approaching the dodger not resulting in a transfer of the pellet, but rather a pivot. There were no observed differences of age or age by timepoint interaction; however, there was a significant main effect of timepoint (Table 3; Fig. 6C). All rats exhibited a greater percentage of dodges earlier (M = 69.30 %, 95 % CI [64.40, 74.10]) in the trial than later (M = 30.40 %, 95 % CI [25.60, 35.20]), thus resulting in an inverse percentage of bracing behavior from early (30.70 %) to late (69.60 %) timepoints in the trial. In general, all rats displayed a switch from dodging to bracing behavior during the consumption of the food items.

To assess overall dodger attention, the nose distance between dodgers and conspecifics at the initiation of food protection behaviors (dodge or brace) was characterized (Fig. 7A & B; Table 3). There was no observed effect of behavior or age by behavior interaction (Fig. 7C). However, there was an observed significant main effect of age with the three-month-old rats (M = 1.86 cm, 95 % CI [1.60, 2.10]) initiating food protection behavior at a greater distance than the ten-month-old rats (M = 1.29 cm, 95 % CI [1.30, 1.80]). Ten-month-old rats exhibited a shorter distance between the noses when the either food protection behavior

Table 1
Open field general movement and stop measures.

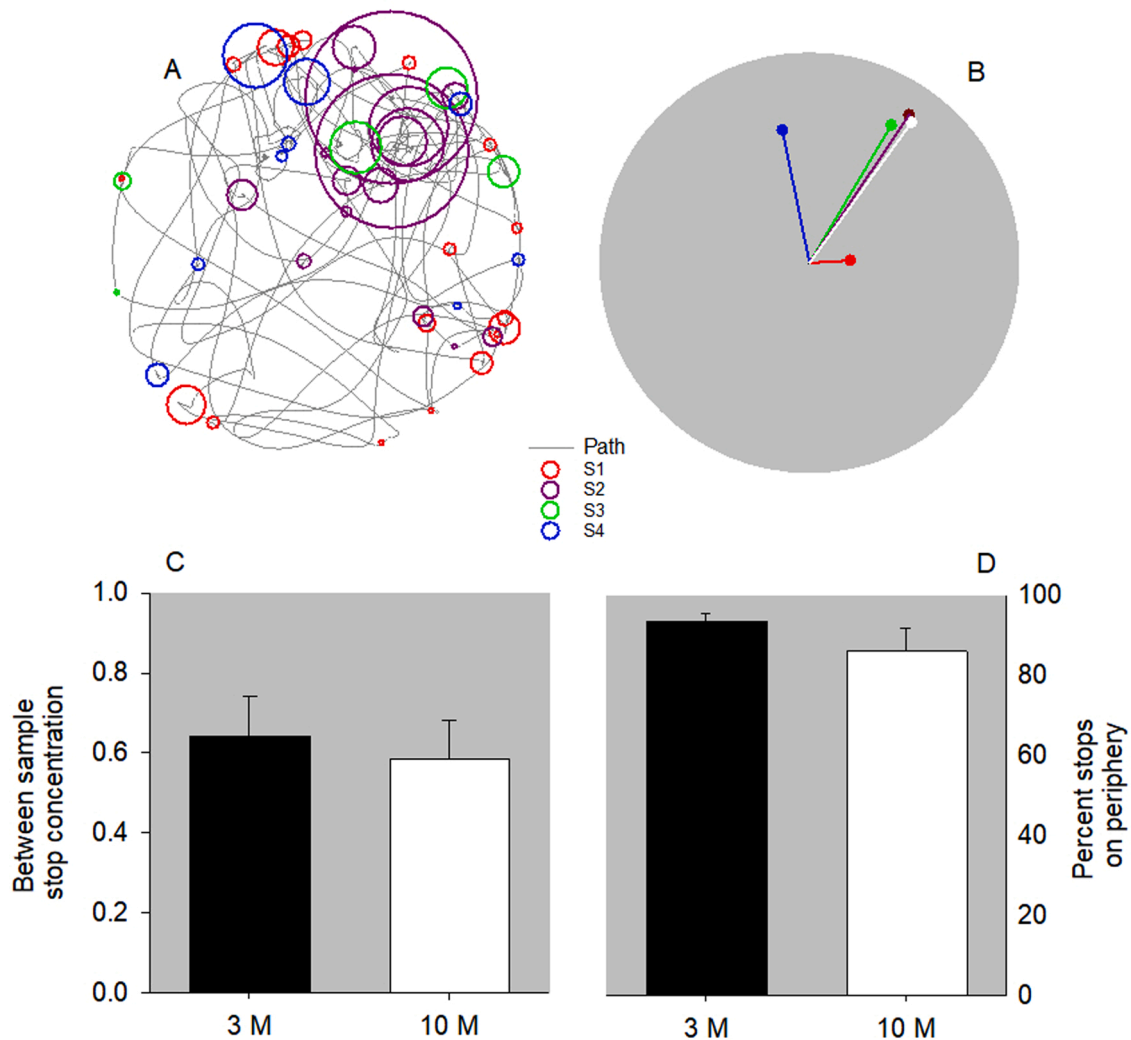|	df	t	p	Cohen's d
Total distance	12	2.624	0.022*	1.403
Average peak speed	12	3.481	0.005*	1.861
Total stop time	12	-1.660	0.123	-0.887
Between sample stop concentration	12	-0.401	0.696	-0.214
Time on periphery	12	-1.243	0.238	-0.664
Average change in heading	12	2.331	0.038*	1.246

Note: * indicates p < .05.

Fig. 2. Position and duration (as represented by the diameter of circles) of stops are plotted for a representative three-month-old rat across the four, five-minute samples (A). Within (color matches sample) and between sample (white line) average heading (direction of line) and concentration (length of line) are plotted for the same representative rat (B). No group differences were observed for between sample stop concentration (C), nor percent of stops on the periphery of the open field (D).

was initiated, relative to three-month-old rats.

4. General discussion

The current study investigated age-related changes in the organization of spontaneously occurring behaviors (see Table 4). In the open field, ten-month-old rats traveled longer distances with faster peak speeds relative to the three-month-old rats. However, groups did not differ in total time spent stopping, clustering of stops, or time spent on the periphery of the table. Most of change in heading along a path occurs during stops. The ten-month-old rats exhibited a larger change in heading during stops that reflected a shift toward a higher prevalence of intermediate heading changes (60–120 degrees). Finally, ten-month-old rats exhibited more circuitous medium and long progressions, relative to the three-month-old rats. Age-related differences in performance were also observed during food protection behaviors. Ten-month-old rats consumed the food item significantly faster (whether the conspecific was present or absent) and exhibited more food protection behaviors, relative to the three-month-old rats. No group differences were observed in the switch from dodging to bracing food protection behaviors during early and late phases of consuming the food item. Finally, ten-month-old rats permitted the robber to approach significantly closer prior to

initiating food protection behavior. As will be discussed below, multiple factors likely contribute to these age-related differences in the organization of open field and food protection behaviors.

4.1. Age-related changes in spatial orientation

Age-related changes in maintaining spatial orientation may be one factor contributing to group differences in the organization of spontaneous behaviors. Animals use environmental and self-movement sources of information to guide movement through an environment (Gallistel, 1990). The source of information used depends on the access and familiarity of environmental cues. In the current study, rat open field behavior was assessed in a novel environment under completely dark conditions, a procedure that would favor using self-movement cues to guide movement (Maaswinkel and Whishaw, 1999). Previous work has illustrated vestibular pathology selectively disrupts components of this open field organization, particularly under completely dark conditions (Banovetz et al., 2021; Blankenship et al., 2017b; Donaldson et al., 2018). Ten-month-old rats exhibited progression topography and change in heading values that parallel the effects associated with vestibular pathology. Future work is needed to determine the extent that age-related changes in vestibular function (Anson and Jeka, 2016; Smith
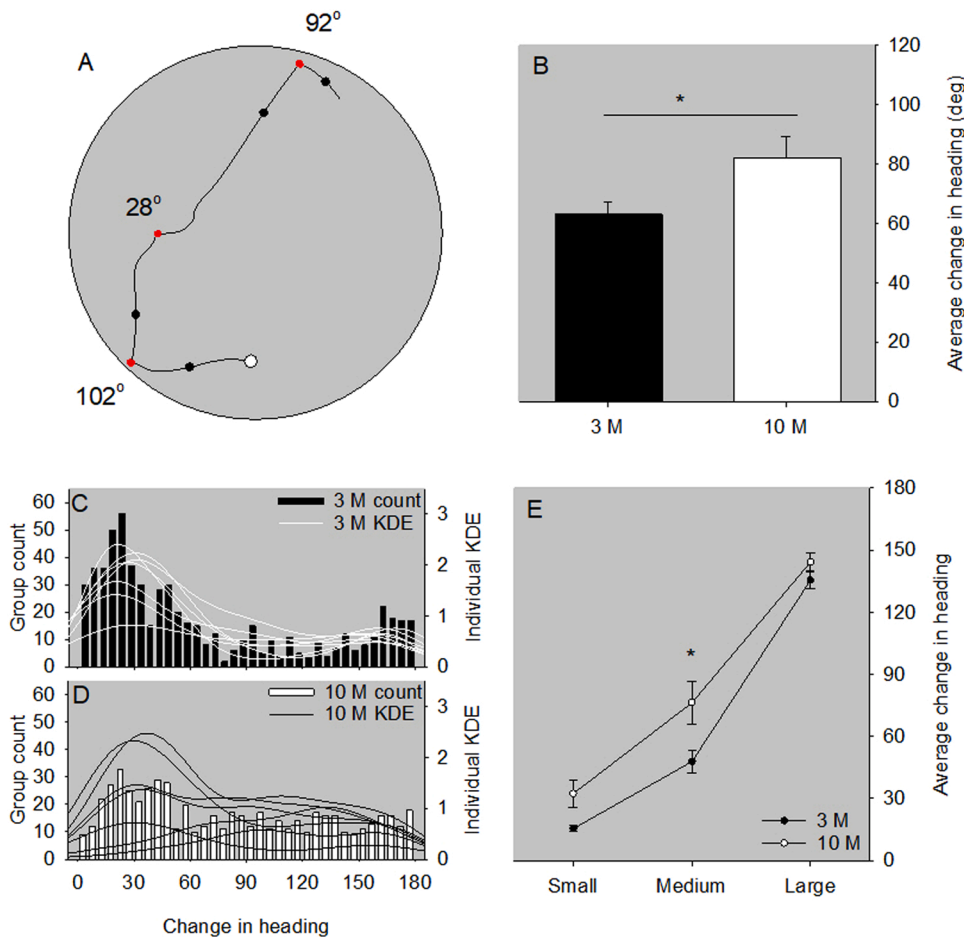
Fig. 3. A sequence of four progressions is plotted for a representative three-month-old (A) rat. The white circles indicate the starting point, the black circles represent the location of the peak speed during the progression, and the red circles represent the stop locations where changes in heading occurred. Degree of change in heading between each stop is indicated near the red circle. Three-month-old rats made smaller changes in heading compared to ten-month-old rats (B). Histograms plot change in heading counts for the three-month (C) and ten-month (D) groups in five-degree steps. Line plots represent each animal's kernel density estimation curve across all possible change in heading values. The group average change in heading is plotted for small, medium, and large angle classes. *p < 0.050.

Table 2
Open field stop and progression measures.

		df	F	p	η2 p
Average change in heading					
	Size	2,24	647.492	<.001*	0.879
	Size x Age	2,24	4.574	0.021*	0.276
	Age	1,12	5.476	0.037*	0.313
Average peak speed					
	Length	2,24	191.207	<.001*	0.941
	Length x Age	2,24	2.730	0.085	0.185
	Age	1,12	14.506	0.002*	0.547
Average path circuity					
	Length	1.014, 12.170	20.092	<.001*+	0.626
	Length x Age	1.014, 12.170	4.771	0.049*	0.284
	Age	1,12	3.505	0.086	0.226

Note: * indicates p < .05, + indicates Levene's test has been violated.

et al., 2019) contribute to the disruptions in the organization of open field behavior. For example, it is possible that age related changes in the anatomy of the vestibular system may produce sufficient heading error to impair maintaining a representation of current position. Alternatively, the hippocampal formation has been implicated in higher level processing of self-movement cues in humans (Philbeck et al., 2004; Wolbers et al., 2007) and rodents (Gorny et al., 2002; Maaswinkel et al., 1999; Wallace and Whishaw, 2003; Winter et al., 2013). Additional work is needed to determine whether age-related changes in

hippocampal function (Morterá and Herculano-Houzel, 2012; Nada et al., 2010; Saito et al., 1994) may influence the accuracy of estimating direction and distance of paths through the environment. Discovering the anatomical basis of age-related changes in self-movement cue processing establishes a foundation to investigate neural basis of spatial disorientation.

Previous work in humans has demonstrated an association between spatial disorientation and spiraling movements (Schaeffer, 1928; Souman et al., 2009; Wallace et al., 2006a). Therefore, it is possible the increase in progression circuity and change in heading observed in the ten-month-old rats may reflect an acute loss of spatial orientation resulting from spiraling movements. In contrast, no group differences were observed in stop clustering. This is consistent with age-related changes in self-movement cue processing not being sufficient to disrupt home base establishment or stability across the session. Further work is needed to examine whether home base stability exhibits age-related changes and the nature of the developmental trajectory.

In general, research investigating age-related changes in spatial orientation has typically focused on tasks that involve using environmental cues to guide movement (Lester et al., 2017). This work has demonstrated that humans (Driscoll et al., 2005) and rats (McLay et al., 1999) exhibit age-related declines in place learning performance on analogues of the Morris water task. This age-related decline in performance is has been attributed to a shift in the strategy applied to environment cue use (Rodgers et al., 2012). Younger human participants tend to encode goal position relative an allocentric reference frame, or cognitive map. In contrast, older human participants shift to using an egocentric reference frame, or route strategy, to encode the position of a goal. However, age-related changes in performance have also been observed on egocentric refence frame tasks (Wilkniss et al., 1997).
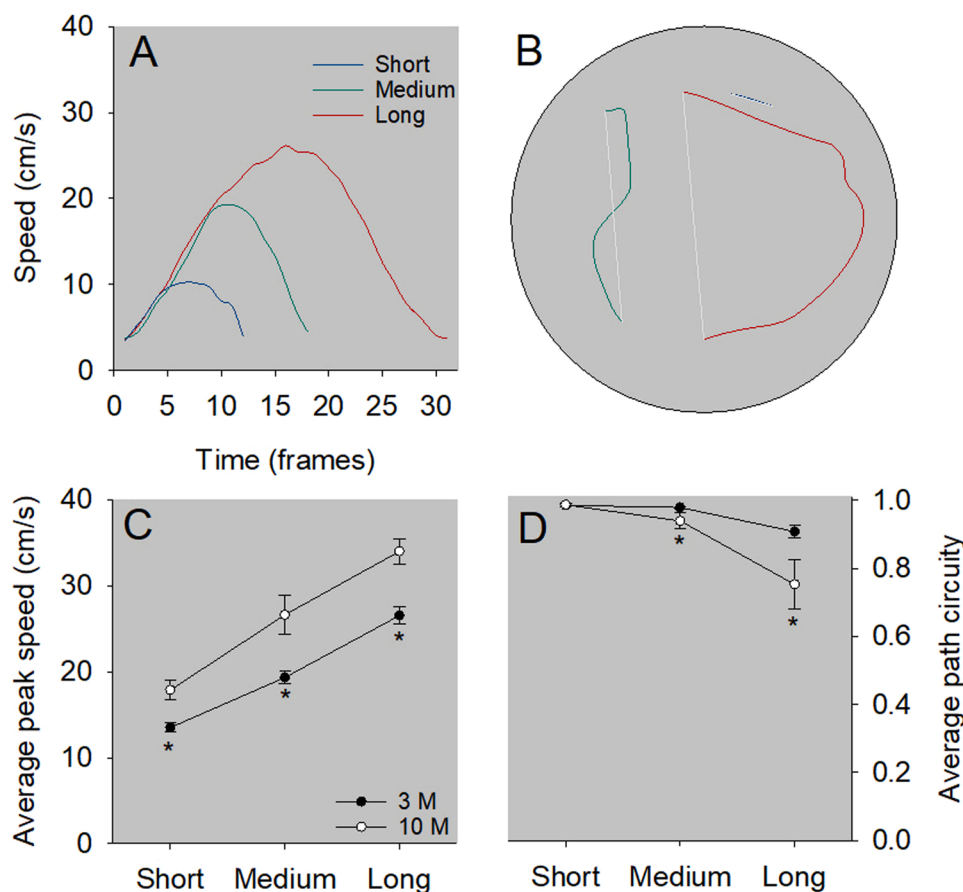
Fig. 4. A representative long (red), medium (green), and short (blue) progression speed is plotted for a representative three-month-old rat (A). The path circuity observed for a respective long (red), medium (green), and short (blue) is plotted with the Euclidean path marked in white (B). Both groups decreased peak speeds as progression class shortened with three-month-old rats maintaining significantly lower peak speeds compared to ten-month-old rats (C). Additionally, both groups on average had relatively non-circuitous progressions; however, differences emerged dependent on length class of the progression, and three-month-old rats trended toward less path circuity in long and medium progressions compared to ten-month-old rats (D). *p < 0.050.

observed in the distance between the noses prior to initiation of a food protection behavior. Ten-month-old rats let the conspecific get closer prior to initiating a food protection behavior, relative to the three-month-old rats. This observation may reflect a subtle deficit in processing environmental cues within the egocentric refence frame. Further work is needed to characterize the trajectory of this age-related change and whether thefts are closely linked.

4.2. Role of motivation in spontaneous behaviors

Several observations from the current study suggest a potential role for motivation in influencing the organization of spontaneous behaviors. For example, ten-month-old rats consumed the food item faster than the three-month-old rats, independent of conspecific's presence. It is unlikely that the age range used in the current study was sufficient to elicit group differences related to energy metabolism (McCarter and Palmer, 1992) or incentive motivation (Harb et al., 2014). In contrast, food restriction procedures have been shown to significantly influence both of these factors (Anderson et al., 2013; Selman et al., 2005). Therefore, it is possible that the increased duration in food restriction experienced by the ten-month-old rats in the current study increased metabolism rate and incentive value sufficiently to influence consumption rate of the food item. An increase in the motivation to consume the food item would also be expected to increase the distance between noses prior to initiating a food protection behavior. However, an opposite pattern of results was observed in the current study; ten-month-old rats let the conspecific get closer prior to initiating a food protection behavior. Therefore, not all group differences in food protection behavior can be attributed to varied levels of motivation.

Motivational factors may have also influenced characteristics of open field behavior. For example, previous work demonstrated that food
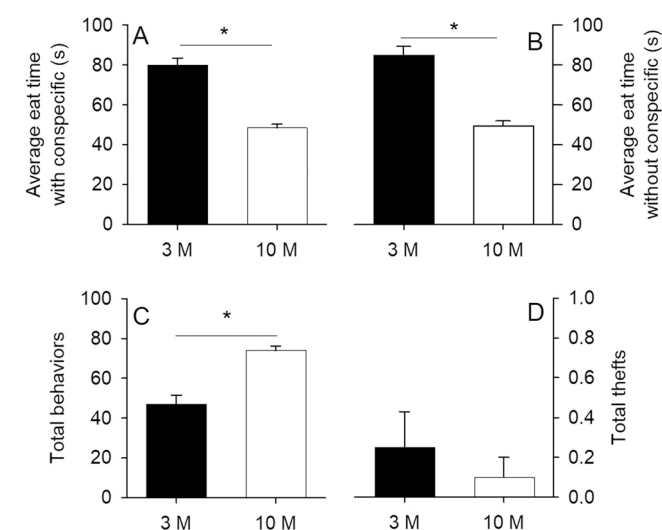

Fig. 5. Average eat time (s) is plotted with (A) and without (B) a conspecific by age. The total number of food protection behaviors are plotted by age (C) with the ten-month-old rats exhibiting significantly more behaviors than the three-month-old rats. The total number of thefts is plotted by age (D). *p < 0.050.

Further, encoding a stable goal position relative to an egocentric reference frame is more challenging when exposed to multiple starting locations than one start location. Food protection behavior depends on responding within an egocentric reference frame to a conspecific approaching from multiple directions. Although no group differences were observed in food item thefts, significant age-related changes were
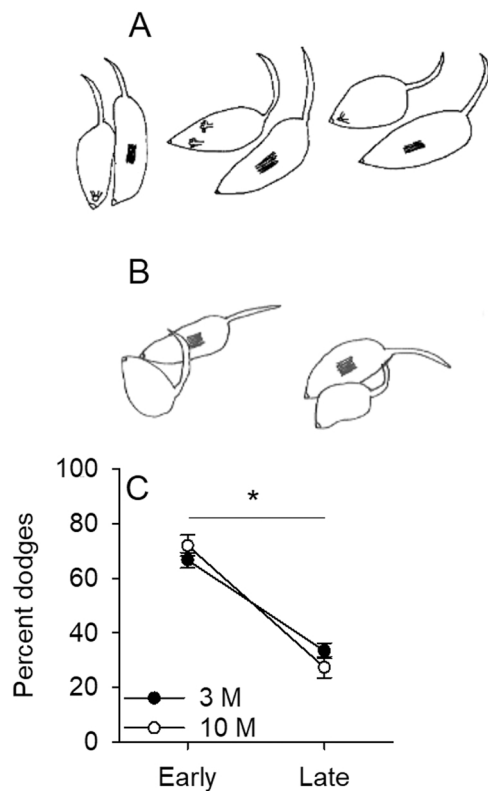
Fig. 6. A representative dodge (A) is displayed with the dodger (unmarked belly) transferring the pellet from their forelimbs to their mouth while executing a full body turn, resulting in their forelimbs touching the floor. Additionally, a representative brace (B) is depicted with the conspecific approaching the dodger not resulting in a transfer of the pellet, but rather a pivot. The percent of doges is plotted across early and late timepoints in the trial, grouped by age (C). All rats displayed a decrease in percent dodging, and subsequent increase in percent of bracing, from early to late timepoints.

Table 3

Food protection behaviors.

		df	F	p	η_p^2
Percent dodges					
	Timepoint	1, 20	70.385	<0.001*	0.779
	Timepoint x Age	1, 20	1.525	0.231	0.071
	Age	1, 20	2.680	0.117	0.118
Average nose distance					
	Behavior	1, 20	0.721	0.406	0.037
	Behavior x Age	1, 20	0.888	0.358	0.045
	Age	1, 20	4.944	0.039*	0.206

Note: * indicates p < .05.

restriction elicits hyperactivity in rodents (Cornish and Mrosovsky, 1965; Finger, 1951; Hall and Hanford, 1954; Pirke et al., 1993). Specifically, it is possible the prolonged food restriction experienced by the ten-month-old group contributed to the group differences in total distance traveled. Total distance traveled is a general measure of activity and has been dissociated from the open field spatial orientation variables. First, mice have been observed to travel longer distances relative to rats; however, both species exhibited similar progression path circuity and change in heading values (Donaldson et al., 2019). Next, vestibular pathology has been observed to influence progression path circuity and change in heading values but not the total distance traveled between groups (Banovetz et al., 2021). These observations demonstrate that multiple factors contribute to the organization of spontaneous behavior, and their influences can be dissociated.
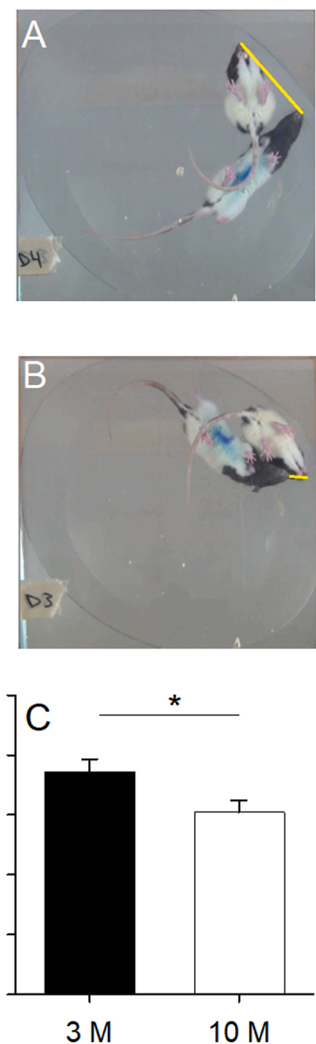

Fig. 7. Representative nose distances (yellow lines) from dodger and conspecific are displayed for long (A) and short (B) distances. The average nose distance (cm) is plotted by age group with the ten-month-old rats initiating food protection behaviors when the conspecifics were at a shorter distance. *p < 0.050.

Table 4

Summary of performance.

	Group difference	Direction of effect
Open field measures		
Total distance	Yes	10 M longer
Peak speed	Yes	10 M faster
Stop time	No	
Between PoC	No	
Time on periphery	No	
Change in heading	Yes	10 M larger
Progression peak speed	Yes	10 M faster
Progression path circuity	Yes	10 M more circuitous
Food protection measures		
Time to eat with conspecific	Yes	10 M faster
Time to eat without conspecific	Yes	10 M faster
Number of food protection behaviors	Yes	10 M more
Total thefts	No	
Percent dodges	No	
Distance between noses	Yes	10 M shorter

4.3. Limitations

The current work describes group differences in the organization of two spontaneously occurring behaviors. Several aspects of the current study limit the inferences that can be drawn from the results. First, this pattern of results may depend on the limited range of movement afforded by standard laboratory housing conditions. The decreased range of movement may have attenuated the development of neural systems involved in maintaining spatial orientation or decreased the resistance of these systems to the effects of senescence. For example, the scale of the habitat has been shown to influence place field size or neural representation of space (Geva-Sagiv et al., 2015). In addition, large scale migratory behaviors in African elephants are typically guided by the eldest female or matriarch (McComb et al., 2011). Both observations are consistent with habitat characteristics influencing neural and behavioral aspects of spatial orientation. Further work is needed to examine whether environmental enrichment (habitat size and social structure) may influence the trajectory of age-related changes in open field or food protection behaviors.

The current study was conducted with three-month-old and ten-month-old female rats. Previous work has not observed sexual dimorphism related to spatial orientation variables (i.e., progression path circuity and change in heading) in the open field (Osterlund Oltmanns et al., 2021). However, sexual dimorphisms in the anatomy of the rodent (Ayyildiz et al., 2008) and human (Marcus et al., 2013) vestibular systems have been observed. In addition, an increased prevalence of vestibular pathology has been reported in human females (Smith et al., 2019). Therefore, the age-related differences in performance reported in the current study may not generalize to the developmental trajectory in male rats.

4.4. Conclusion

The current study evaluated differences in movement organization during open field behavior and food protection in three- and ten-month-old female rats. In the open field, ten-month-old rats traveled longer distances with faster peak speeds, exhibited larger changes in heading during stops, and followed more circuitous progressions. During food protection, ten-month-old rats were able to protect the food item and let the conspecific approach closer prior to initiating a food protection behavior. These observations are consistent with age-related changes in processing self-movement or egocentric cues, and motivational factors that occur earlier in the lifespan of the rat than have been previous reported. Future work is needed to evaluate if differences in performance can be attributed to neural systems supporting this processing, such as the hippocampus or cortex.

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