Behavioural Processes 212 (2022) 104934

Contents lists available at ScienceDirect

Behavioural Processes

journal homepage: www.elsevier.com/locate/behavproc

Environmental enrichment accelerates the acquisition of schedule-induced drinking in rats

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ARTICLE INFO

Keywords:
Environmental enrichment
Schedule-induced drinking
Housing conditions
Social stimulation
Physical stimulation
Rats

ABSTRACT

Environmental enrichment (EE) provides an improvement in the housing conditions of experimental animals, such as laboratory rats, with greater physical and social stimulation through toys and company in the home cages. Its use is known to influence performance of experimental protocols, but these effects have not been well determined in the schedule-induced drinking (SID) procedure. The main goal of this study was to investigate the effects of EE on the acquisition of SID in 24 12-week-old male Wistar rats, divided into two groups, a group with EE housed with toys and companions, and a group without enrichment in individual housing conditions without toys (social isolation and no environmental enrichment, INEE). A total of 25 sessions, under a fixed time 30 s food reinforcement schedule and with access to water in the experimental chambers were carried out. Sessions lasted 30 min. The results showed that the EE group developed faster the excessive drinking pattern of SID, and drank to higher levels, than the INEE group. The greater development of SID in the EE group contradicts the view of schedule-induced behavior as linked to stress reduction and better suits with the conception of induction related to positive reinforcement.

1. Introduction

Ensuring the well-being of animals is crucial for scientific research. The benefits of an enriched environment (EE) have been recognized since the 1920s (Yerkes, 1925), but EE in animal housing has only recently gained importance in laboratory work. Improving housing conditions is essential, as EE has a significant impact, including strengthening the immune system, increasing neuronal density, and enhancing learning ability (Renner and Rosenzweig, 1987). Furthermore, social isolation in rodents, considered social animals by nature, has negative effects on behavior, cognition, neurobiology, immune function, physiological health, and stress reaction (Fone and Porkess, 2008; Krimberg et al., 2022; Lukkes et al., 2009).

Rodent enrichment in laboratory settings typically involves using toys such as nesting materials, plastic tunnels and paper pieces for physical stimulation (Van de Weerd et al., 1997; Young et al., 2003). These toys can be permanently provided or rotated to ensure fairness and avoid competition (Hubrecht, 1993). Social stimulation is achieved by increasing contact with research staff and facilitating interaction among peers (Shepherdson, 1998).

The current literature on EE focuses on studying its effects on cerebral, neuroendocrine, and immune changes (Johansson and Belichenko, 2002). Some studies have also explored its influence on learning, self-control, and problem-solving abilities (Marashi et al., 2003; Wang et al., 2017). Research suggests that providing social and environmental enrichment can have a protective effect against food- and drug-seeking behaviors (Galaj et al., 2020; Grimm and Sauter, 2020; Malone et al., 2022). Additionally, providing a positive and stimulating environment results beneficial against several psychiatric disorders, such as major depression, anxiety or autism spectrum disorder (Kimura et al., 2021; Kuznetsova et al., 2020; Manosso et al., 2022). The neurobiological mechanisms underlying these positive effects of environmental and social enrichment in rodents are complex, and some of the implicated processes include: i) neurogenesis in specific brain regions, such as the hippocampus, associated with improved learning, memory, and emotional regulation (Beauquis et al., (n.d.); Chrusch et al. (2023); Kempermann (2019); Loisy et al. (2023)); ii) increased synaptic plasticity, facilitating the formation of new neural pathways promoting

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https://doi.org/10.1016/j.beproc.2023.104934
Received 22 November 2022; Received in revised form 10 August 2023; Accepted 29 August 2023

learning, social adaptive behaviors and cognitive flexibility (Gelfo, 2019; Gubert and Hannan, 2019; Kentner et al., 2019); and iii) modulation of the activity of various neurotransmitter systems, including dopamine, serotonin, GABA and glutamate, that play crucial roles in regulating mood, reward and motivation, contributing to overall behavioral well-being (Brenes et al., 2008; Loisy et al., 2023; Malone et al., 2022; Zhu et al., 2005).

On the other hand, stress in laboratory rodents is often evidenced by the emergence of stereotypies, excessive and non-beneficial behaviors (Gross et al., 2012). Access to EE has been shown to decrease stereotypies in rodents (Würbel et al., 1998). Studies have explored the role of stereotypies in humans with autism spectrum disorder, suggesting that they are operant behaviors maintained by self-produced sensory stimulation or non-programmed positive reinforcers (Carr, 1977; Eikeseth and Grung, 2017; Hanley et al., 2000; Lovaas et al., 1987; Potter et al., 2013). Increasing EE, such as providing more interactive toys, reduces stereotyped behaviors and enhances behavioral variability (Sidener et al., 2005). Similar to humans, EE should promote species-specific behaviors, diminish stereotypies, and foster healthy behavioral diversity in other animals.

In the same way that stereotyped behaviors can be the product of unscheduled reinforcement, it has been proposed that schedule-induced behaviors (SIB) (i.e., adjunctive behavior) are those that are developed excessively in an intermittent reinforcement schedule, without an explicit contingency with the reinforcer (Killeen and Pellón, 2013; Pellón et al., 2020). The most studied SIB is schedule-induced drinking (SID), first described by Falk (1961) (i.e. polydipsia), who found that rats that had access to a bottle of water during the experimental session developed a pattern of excessive water consumption when food was intermittently administrated. Drinking occurred just after the delivery of the reinforcer, it was not a product of thirst, and there was no programmed contingency with its occurrence. Despite the excessiveness of SID -and other SIBs-, it should not be considered a stereotypy produced by stress, as it occurs under specific experimental circumstances (Ardoy and Pellón, 2004) and is dependent on the intermittent delivery of food (e.g., Gutiérrez-Ferre and Pellón, 2019; Lamas and Pellón, 1997).

SID has been developed using different reinforcement schedules than those initially proposed by Falk (Pellón, 1990). This has led to varying interpretations regarding its origin and development (see Baum and Aparicio, 2020; Falk, 1977; Killeen and Pellón, 2013; Staddon, 1977). Initially, SID was considered a behavior separate from operant behavior because it was believed to be induced by the reinforcer but not reinforced by it (Falk, 1971; Staddon, 1977). However, Killeen and Pellón (2013) argued that an explicit contingency is not necessary for behavior acquisition, and temporal proximity between the response and the reinforcer is sufficient for behavior to be acquired. Therefore, there is no real obstacle in considering SID (and other SIBs) as operant behavior. The intermittent nature of reinforcement schedules is enough for the development and maintenance of SID, although explicit licking-reinforcing contingencies can improve its development (Álvarez et al., 2016). Alternatively, Baum and his colleagues (Baum, 2012; Baum and Aparicio, 2020) suggest that behaviors are not solely acquired or maintained through reinforcement, but rather induced by phylogenetically important events (PIE; i.e., reinforcers).

There is limited research on the impact of EE on adjunctive behaviors. Jones et al. (1989) compared the development of SID in rats raised in isolation or social groups, as well as individually or group-housed adult rats. Group-reared rats consumed more water, but no differences were found in licking behavior, an effect that should be further investigated. Among adult rats with different social conditions, no differences were observed in drinking or licking. No other studies have tested the effect of EE on SID acquisition. The study also lacked a detailed description or presentation of the temporal distribution of behaviors, emphasizing the need for additional experimental data.

The main goal of the present study was to observe the effect of two housing conditions on the development and distribution of SID: isolation and no environmental enrichment, and group housing with physical EE. It has been previously suggested that the intermittent delivery of reinforcement generates an increase in behaviors related to it (Baum, 2012; Killeen, 1975), thus increasing the probability that they will be reinforced when they occur in temporal proximity to the reinforcer (Killeen and Pellón, 2013; Ruiz et al., 2016). Considering that EE tends to promote a greater amount of exploratory behaviors in animals (see Jones et al., 1989), and in accordance with what has been observed in patients of the autistic spectrum (Sidener et al., 2005), it is predicted that those subjects who have access to EE will have a greater behavioral variability that translates into a faster SID development.

The current regulations on protection of animals used for scientific purposes included in the Directive 2010/63/EU of the European Parliament (European Medicines Agency, 2010) consider EE as a mandatory requirement. Given that EE produces effects on the behavior of animals and the variability of the studied variables (Bayne and Würbel, 2014; Toth et al., 2011), it is important to consider whether its use influences the performance of rats in standard procedures. Therefore, a second goal of the present study was to establish the effects of EE so that they can be considered when comparing results using old protocols in which rats were isolated and did not have access to physical EE with the current EE protocol, in which group-housing and access to physical EE is recommended.

2. Method

2.1. Subjects

Twenty-four male Wistar rats (Charles River, Lyon, France) were used as subjects. The subjects were seven weeks old upon arrival at the laboratory, and were housed in groups of four, with free access to a water bottle and food (LabDiet; BrentWood, MO, USA). The environmental conditions of the facilities were maintained with an approximate temperature of 22° C, a relative humidity of 55%, and 12-hour light-dark conditions, starting the light period at 8:00 am.

Rats were randomly divided into two groups of 12 subjects. In the control group (isolation and no environmental enrichment, INEE), the subjects were distributed into individual home cages when they were 8 weeks old and stayed in such conditions throughout the experiment. The home-cages were made of transparent polycarbonate, measuring 18 cm × 32 cm x 20.5 cm, with a metal grid roof that had a curved section for the food container and a metal nozzle to insert the water bottle. The rats lived in groups up to this point. The subjects of the experimental group (environmental enrichment, EE) were kept housed in groups of four, in home-cages measuring 60 cm × 38 cm x 20.5 cm with access to a variety of enriching objects/materials (see below).

Over the course of a week without food restriction, the theoretical weight of each subject was calculated with reference to the standard growth curve of the strain, and access to food was restricted to reduce the weight of the rats and maintain them between 80% and 90%. Water was always available in the home-cages. The subjects had a time limit of 1–2 h for food intake, which varied according to changes in weight considering the criterion. In the EE group, some subjects showed competitive behavior for food, so they were separated at mealtimes when necessary to maintain their weights. Once the weight criterion was reached, the procedure began. At this time, the rats were 10 weeks old and had a mean weight of 294.5 ± 31 g, in the INEE group, and 295 ± 40 g, in the EE group.

All procedures were carried out in accordance with Directive 2010/63 of the European Union, with Royal Decree 53/2013 on the protection of animals used for experimentation to minimize stress, and with the corresponding authorization from the Community of Madrid with reference PROEX 077/18.

2.2. Apparatus

To carry out the experiment, experimental chambers, an interface, and specific computer software (MED-PC-IV) installed on a Windows 7 operating system, were used. The connection between these elements allowed for a precise recording of spout licks and magazine entrances during the experimental sessions. A total of eight Letica-LI 836 chambers measuring 29 cm × 24.5 cm × 35.5 cm were used. Each chamber was contained within another larger wooden box for soundproofing, equipped with 25 W ambient lighting, a ventilation system that produced a background noise of 60 dB to mask out external noises, and a small observation window in its front panel.

The conditioning chambers had black polycarbonate rear and side walls, transparent polycarbonate front and top walls, and an aluminum side wall. In the latter, at 3.7 cm from the ground, was the magazine aperture, which allowed the registration of entries through a laser sensor, and connected to it, a 45 mg food-pellets dispenser (Bio-Serv, Frenchtown, NJ, USA). In the rear wall, there was a 3.2 cm × 3.9 cm opening, located 20 cm from the front of the panel and 7 cm from the floor, from which rats could access a water bottle. The bottle was connected to a metallic nipple capable of detecting the contact of the rat's tongue with the nipple. In this way, the recording of each subject's licking was enabled in each of the sessions. The base of each chamber was made of metal rods, and below them, a removable tray with sawdust.

2.3. Procedure

2.3.1. Environmental enrichment

In addition to the social stimulation to which they were exposed by living with 3 other subjects in their home cages, the EE subjects were given fixed and rotating physical stimulation (toys). The fixed stimulation consisted of red polycarbonate tunnels (15.5 cm long x 7.5 cm in diameter; Sodispan Product Code GZRTUN) that were always available in the home-cages of the EE subjects, but their specific location within the home-cage was changed daily. The rotating stimulation consisted of inserting one wooden stick for each rat (height: 5 cm, base 1 × 1 cm; Sodispan Product Code CS3C15) into the cages on Mondays, and paper wool on Fridays (enough for all subjects to have access to them; Sodispan Product Code CS1C02). Pictures of the EE protocol are included in the Appendix.

2.3.2. Schedule-induced drinking procedure

The procedure consisted of 25 sessions that lasted 30 min. Food-pellets were delivered according to a fixed time (FT) 30 s reinforcement schedule, in which, every 30 s, subjects received a single food pellet without the need to make any kind of response to obtain it. Each subject received a total of 60 food-pellets in each session. A bottle of water was always available in the experimental chambers. After the sessions, the rats were returned to their respective home cages and were fed, as described above, 20 min after the end of the sessions.

2.4. Data Analysis

The measures calculated were response rate, time of peak, width of peak and time of transition. The analyses were carried out using R on RStudio (R Core Team, 2021; RStudio Team, 2020), Macros on Excel and Python on Pycharm (JetBrains, 2021). Response rates per minute were calculated for licks and magazine entries. To calculate the time and width of the peak and the time of transition, the distribution of responses throughout the intervals were calculated for each subject and session in 1-s bins using the package MedPCPy (Maldonado et al., 2023) on Python.

The time and width of the peak were estimated by fitting a Gaussian function to individual distributions in 5-sessions blocks:

$$A \times \left(f(t, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \right),$$

where, A is a free parameter that converts Gaussian probabilities onto the same scale of individual response rates, t is the time from the beginning of the interval (in seconds), μ is the time of the peak (i.e., the mean of the distribution), and σ is the width of the peak (i.e., the standard deviation of the distribution). The function was fitted to the data using the nlmrt package (Nash, 2016) on R which fits non-linear functions by attempting to find the minimum of the residual sum of squares. The starting values were $A = 1000$, $t = 15$ and $\sigma = 5$, with lower bounds of 100, 1 and 3, and upper bounds of 100000, 10 and 30, respectively for each parameter. The function was fitted adequately to most 5-session blocks; see Table A1 for details.

Lastly, the time of transition between responses was calculated as the time in the interval in which the rate of magazine-entering per second was higher than the rate of licking per second. This was calculated for each subject and session using an Excel macro.

The differences in the rate of licks and magazine entries, the time and width of the peak, and the time of transition, between the EE and INEE groups were compared using Bayesian Linear Mixed-Effects Models (BLMM)[2] by means of the brms package (Bürkner, 2018, 2017) on R. A null model was constructed for each measure, and then further models were developed and compared with each other using Bayes factors (BFs). Default priors provided by brms were used in the analysis. The best-fitting model for each measure, along with the BF of the comparison between that model and its null model, is included in Table 1. The estimated parameters of the model were obtained by running 4 chains of 2000 simulations, each with a 1000-iterations warmup, thus obtaining a posterior distribution of 4000 samples for each parameter of each model, except for the model for magazine entries, that included 8000 samples, as its chains were of 3000 simulations with a 1000-iterations warmup. The reliability of the models was evaluated using the $\widehat{R}$ statistic, and all estimated parameters fell into the range of $\widehat{R} = 1 \pm 0.1$, thus indicating convergence (Sorensen et al., 2016). The expected value (i.e., the mean of the posterior distribution), the standard error and the 95% credible interval (CI) were calculated for each parameter of the model (intercept and slopes) and are also included in Table 1. Finally, the posterior probability (P(δ)) of slopes is included in the last column of Table 1. The P(δ) of a slope to be more (or less) than zero in 95% of samples was interpreted as compelling evidence for that difference.

Data, scripts used for all analyses, and additional materials including the priors, posterior distributions, and posterior predictive checks for each BLMM can be retrieved from: https://osf.io/b29y3/.

3. Results

Fig. 1 shows licking and magazine entering rates. Licking rate (left panel of Fig. 1) increased throughout the sessions and stabilized towards the end of the experiment. EE rats drank at higher rates throughout the experiment, although the acquisition pattern was similar. The best BLMM included Group as a fixed effect, by-session random slopes for groups, and random intercepts for subjects. The model confirmed that subjects in the EE group drank at higher rates than rats in the INEE group, as there was compelling evidence ($P(\delta) < 0 = .985$) for that difference. Table 2 shows the milliliters of water intake (mean ± SEM) in blocks of 5 sessions that support this result. Magazine-entering rate is depicted in the right panel of Fig. 1. Magazine-entering rate showed a slight increase in the first few sessions but stabilized after session 9

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[2] For more information on the advantages of Linear Mixed-effects Models and the Bayesian approach, see López-Tolsa and Pellón (2021), López-Tolsa et al. (2020), and Young (2018, 2019); and for tutorials see Brown (2021), and Franke and Roettger (2019).

Table 1

Diagnostic and posterior summary statistics of the estimated parameters of the Bayesian Linear Mixed-effects Models.

Model	BF	Parameter	$\hat{R}$	Mean 𝔼	SD 𝔼	2.5% CI	97.5% CI	Posterior probability of slope
Licking rate								
Licks ~ Group + (1 + Group|Session) + (1|Subject)	8.20e^{+90}	Intercept (μ_{EE})	1	89.18	13.54	63.24	115.90	-
		Slope Group (μ_{INEE})	1	-37.84	17.11	-70.99	-3.08	$P(\delta) < 0 = .985$
Magazine-entering rate								
Entries ~ Group + (1|Session) + (1|Subject)	43.70	Intercept (μ_{EE})	1	22.88	2.08	18.96	27.04	-
		Slope Group (μ_{INEE})	1	2.66	3.07	-3.41	8.59	$P(\delta) > 0 = .814$
Time of peak								
Peak ~ Group*Session + (1|Subject)	8.85e^{+26}	Intercept (μ_{EE})	1.01	11.26	0.47	10.33	12.15	-
		Slope Group (μ_{INEE})	1	2.11	0.71	0.75	3.52	$P(\delta) > 0 = .999$
		Slope Ss 6–10	1.01	-1.00	0.33	-1.65	-0.33	$P(\delta) < 0 = 1$
		Slope Ss 11–15	1	-1.55	0.33	-2.20	-0.90	$P(\delta) < 0 = 1$
		Slope Ss 16–20	1	-2.17	0.34	-2.83	-1.51	$P(\delta) < 0 = 1$
		Slope Ss 21–25	1	-2.32	0.33	-2.98	-1.67	$P(\delta) < 0 = .995$
		Slope Group*Ss6–10 (μ)	1.01	-1.35	0.51	-2.38	-0.35	$P(\delta) < 0 = 1$
		Slope Group*Ss11–15 (μ)	1	-1.91	0.50	-2.88	-0.92	$P(\delta) < 0 = 1$
		Slope Group*Ss16–20 (μ)	1	-1.97	0.50	-2.95	-0.98	$P(\delta) < 0 = 1$
		Slope Group*Ss21–25 (μ)	1	-2.16	0.50	-3.14	-1.18	$P(\delta) < 0 = 1$
Width of peak								
Width ~ Group*Session + (1|Subject)	2.56e^{+14}	Intercept (μ_{EE})	1	4.63	0.34	3.98	5.32	-
		Slope Group (μ_{INEE})	1	1.75	0.49	0.78	2.72	$P(\delta) > 0 = .999$
		Slope Ss 6–10	1	-0.54	0.33	-1.20	0.10	$P(\delta) < 0 = .949$
		Slope Ss 11–15	1	-0.39	0.33	-1.02	0.27	$P(\delta) < 0 = .886$
		Slope Ss 16–20	1	-0.76	0.33	-1.40	-0.09	$P(\delta) < 0 = .989$
		Slope Ss 21–25	1	-0.43	0.33	-1.10	0.19	$P(\delta) < 0 = .91$
		Slope Group*Ss6–10 (μ)	1	-1.68	0.48	-2.61	-0.72	$P(\delta) < 0 = .999$
		Slope Group*Ss11–15 (μ)	1	-2.42	0.50	-3.39	-1.44	$P(\delta) < 0 = 1$
		Slope Group*Ss16–20 (μ)	1	-2.28	0.49	-3.23	-1.31	$P(\delta) < 0 = 1$
		Slope Group*Ss21–25 (μ)	1	-2.58	0.49	-3.55	-1.61	$P(\delta) < 0 = 1$
Time of transition								
Time of transition ~ Group*Session + (1|Subject)	1.73e^{+18}	Intercept (μ_{EE})	1	15.38	0.88	13.63	17.08	-
		Slope Group (μ_{INEE})	1	-2.82	1.24	-5.32	-0.32	$P(\delta) < 0 = .987$
		Slope Ss 6–10	1	4.40	0.86	2.68	6.07	$P(\delta) > 0 = 1$
		Slope Ss 11–15	1	4.47	0.91	2.65	6.21	$P(\delta) > 0 = 1$
		Slope Ss 16–20	1	3.93	0.88	2.20	5.64	$P(\delta) > 0 = 1$
		Slope Ss 21–25	1	4.08	0.88	2.32	5.78	$P(\delta) > 0 = 1$
		Slope Group*Ss6–10 (μ)	1	0.02	1.23	-2.41	2.44	$P(\delta) > 0 = .507$
		Slope Group*Ss11–15 (μ)	1	0.93	1.27	-1.60	3.45	$P(\delta) > 0 = .772$
		Slope Group*Ss16–20 (μ)	1	1.14	1.24	-1.27	3.64	$P(\delta) > 0 = .832$
		Slope Group*Ss21–25 (μ)	1	0.72	1.27	-1.75	3.15	$P(\delta) > 0 = .713$

Note. BF = Bayes factor of best-fitting model, compared to null model. 𝔼 = Estimated value. SD = Standard Error. CI = Credible Interval.

throughout the experiment. The BLMM included Group as a fixed effect and random intercepts for subjects and sessions. Although magazine-entering rate was higher for the INEE than for the EE group (slope = 2.66) throughout the experiment, there was not enough evidence for this difference ($P(\delta) > 0 = .814$).

Fig. 2 shows the distribution of licks and magazine entries for both groups in 5-sessions blocks. The distribution of licks shows an increase that began around second 3, coinciding with the post-pellet period, with a maximum peak of licks between seconds 9 and 11 in sessions 1–5 and around seconds 7–8 in sessions 16–25, and then progressively declined until approximately second 20. Licking, as can be observed, was acquired more quickly in the EE group, with greater difference in the initial sessions (graphs from sessions 1–5 and 6–10), and a greater number of licks between seconds 5 and 15. On the other hand, the INEE group did not clearly show this distinctive increase in licking in the first sessions. However, both groups developed SID and the final shape described by the distribution did not differ between groups.

To provide a quantitative analysis of the distribution, a Gaussian function was fitted to individual data, and the time and width of the peak were estimated for each subject in each 5-sessions block. Panels a and b in Fig. 3 show the time of peak and its width for each group in each sessions-block. Regarding the time of the peak, it can be observed that it occurred later in the first block of sessions and earlier in sessions 21–25, also differences between groups decreased as training increased, supporting the statement that EE subjects acquired the final distribution more quickly than the INEE group.

The best BLMM of time of peak included the interaction of Group and Block of sessions as fixed effect and random intercepts for subjects. There was compelling evidence for the slope of the interaction of Group and each block of sessions ($P(\delta) < 0 = 1$ in all cases, see Table 1), indicating that differences between groups changed among the blocks of sessions. Similarly, the best BLMM of width included the interaction of Group and Block of sessions as fixed effect and random intercepts for subjects. Also, differences between groups changed throughout the blocks of sessions, as supported by the compelling evidence for the slope of the interaction to be less than zero ($P(\delta) < 0 = .999$ for block of

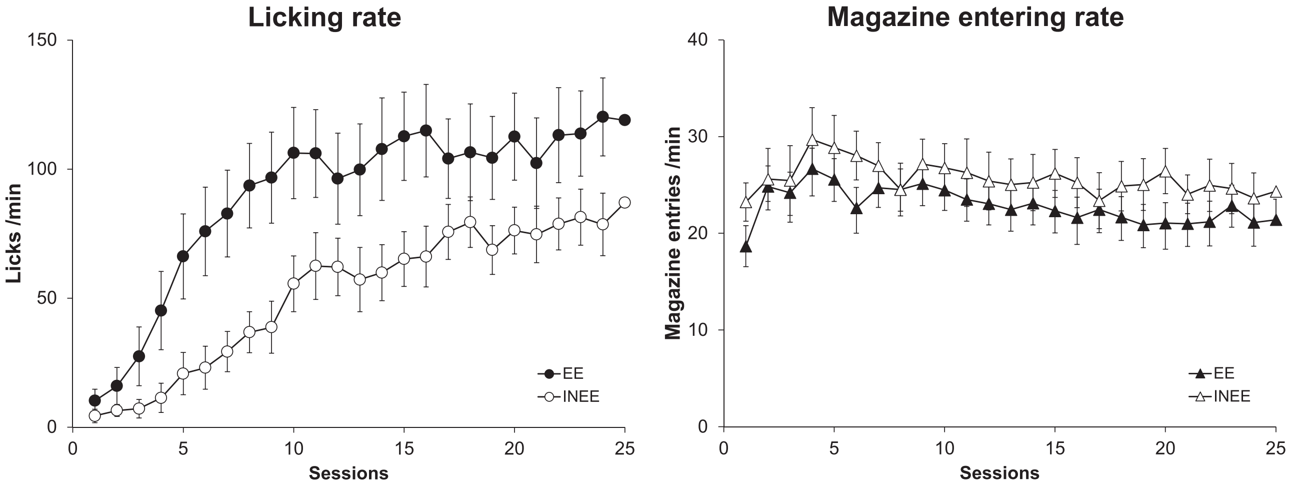

Fig. 1. Licking and magazine-entering rates throughout the experiment. Licking rate (left panel) and magazine-entering rate (right panel) (mean ± SEM) for the environmental enrichment group (EE, n = 12), represented with black symbols, and the isolated and no environmental enrichment group (INEE, n = 12), represented with white symbols, throughout the 25 sessions of the experiment.

Table 2
Water consumption throughout blocks of sessions.

Water intake (ml)					
Sessions	1–5	6–10	11–15	16–20	21–25
Group EE	8.02 ± 1.22	16.12 ± 2.37	21.45 ± 2.58	21.72 ± 2.74	22.52 ± 3.26
Group INEE	4.35 ± 0.77	8.12 ± 1.50	11.98 ± 1.90	13.92 ± 1.80	15.67 ± 1.76

Mean ± SEM

sessions 6–10, and P(δ) < 0 = 1 for the last three blocks, see Table 1).

Additional to analyzing the distribution of licks, its relation to magazine entries was calculated trough the time of transition from licks to magazine entries. The bottom panel in Fig. 3 shows how as sessions progressed, the time of transition occurred later in the interval, and that it occurred later for the EE group, than for the INEE group, as to be expected given the differences between groups in the distribution of licks. The best BLMM of time of transition included the interaction of Group and Block of sessions as fixed effects, and random intercepts for subjects, nevertheless, there was not enough evidence for the interaction of Group and each block of sessions to be greater than zero (see Table 1).

4. Discussion

This study introduced social and physical enrichment (the EE group) or isolation without enrichment (the INEE group) to animals at 8 weeks of age (young adults), 14 days prior to the behavioral SID test, and maintained these conditions for a total duration of 39 days. The results demonstrated that social and physical enrichment positively influenced task acquisition and performance, while social isolation and deprivation of an enriched environment result in slower acquisition and a lower rate of licking.

The aim of this experiment was to study the effect of EE on the development and distribution of SID, and results showed that the EE group not only acquired the behavior faster, but also licked at higher rates than the INEE group. These results expand those previously obtained by Jones et al. (1989), who reported lower water intake in isolation-reared than in group-reared rats, but curiously no differences in licking rates. This lack of differences was attributed to a decrease in lick efficiency (licks/ml) in the isolation-reared rats, thus resulting in them licking the same for a less amount of water, so it might be related to the critical age at which EE was manipulated in their study, or to the lack of physical enrichment. In addition, the present results support an apparently exclusive effect of EE on SID over magazine entries, in this study, and over panel presses, in Jones et al.'s (1989) study. Although differences in magazine entries in this study were not significant, they still consistently occurred at higher rates for the INEE than for the EE group, in line with the notion that behaviors compete and shape each other's distributions (López-Tolsa and Pellón, 2021; Pellón and Killeen, 2015), even though such competition cannot exclusively explain differences in licking rates here.

Isolation rearing, which deprives individuals of social interactions during development, can lead to a deficiency in essential physical and social stimuli necessary for proper neural development (Adams and Rosenkranz, 2016). Additionally, it can have behavioral consequences, such as impaired social recognition (Kercmar et al., 2011; Okada et al., 2015; Thor et al., 1982), anxiety (Ago et al., 2007; Amiri et al., 2015), or depression (Amiri et al., 2015). These deficits have been demonstrated not only when social isolation takes place in an early stage but also when it occurs later in adolescence (Medendorp et al., 2018) or adulthood (Cuenya et al., 2012; Ieraci et al., 2016; Zorzo et al., 2019), as it was the case of the INEE group here.

Despite the differences in acquisition speed and rate of licking, both groups showed the same distribution of licking during the inter-food interval, which was also similar to what is typically reported in SID procedures (Álvarez et al., 2016) and to what Jones et al. (1989) reported. This finding suggests that EE does not seem to affect the temporal learning of subjects (Ruiz et al., 2016). Additionally, it would explain the lack of differences in the number of magazine entries, as, regardless of the amount of drinking, both groups showed the same distribution of the different types of behaviors during the interval (Baum, 2015; López-Tolsa and Pellón, 2021; Pellón and Killeen, 2015; Ruiz et al., 2016).

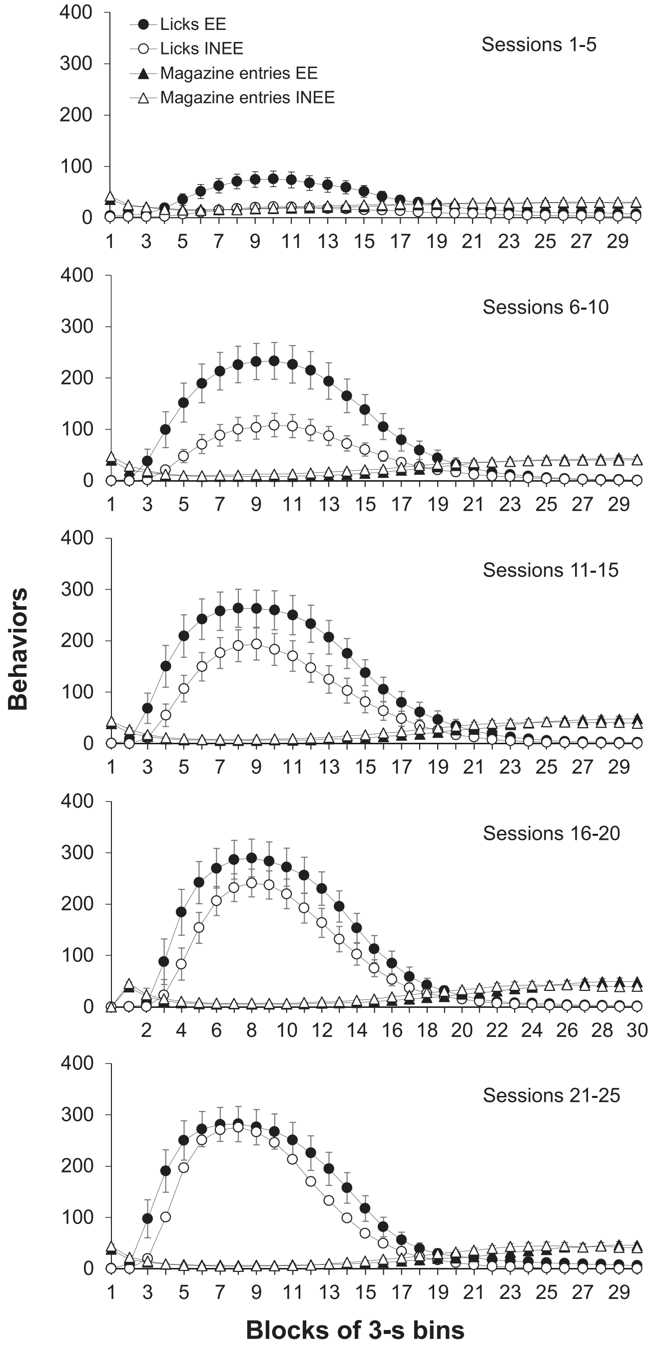

Fig. 2. Licking and magazine-entering distributions during the inter-food interval. Number of licks (circles) and magazine entries (triangles) (mean ± SEM) for the environmental enrichment group (EE, n = 12), represented with black symbols, and the isolation and no environmental enrichment group (INEE, n = 12), represented with white symbols, in blocks of 3 s bins during the interval between food deliveries of a FT 30 s reinforcement schedule. Data represented in blocks of 5 sessions.

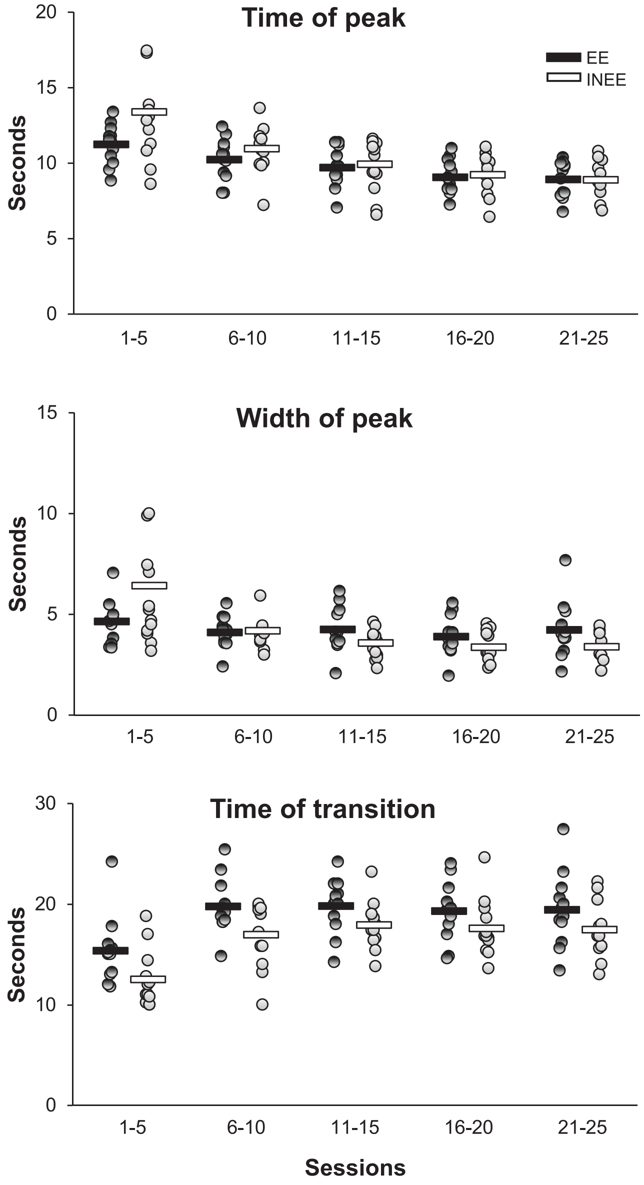

Fig. 3. Comparisons of time of the peak, width of the peak, and time of transition, for each 5-sessions blocks. Time of the peak, width of the peak, and time of transition, for the environmental enrichment group (EE, n = 12), represented with black symbols, and the isolation and no environmental enrichment group (INEE, n = 12), represented by white symbols. Rectangles represent the mean, and circles represent individual data. Data are represented in blocks of 5 sessions.

It is generally accepted that EE increases exploration and species-specific behaviors and the level of alertness of the animal (Council of Europe, 1997), which, together with the intermittent delivery of reinforcers, should increase the occurrence of behaviors related to it (Baum, 2012; Killeen, 1975). For example, rats usually drink water after food is delivered, so an increase in exploration and activity in general should increase the probability that the rats of the EE group, when exploring the operant chamber, would encounter the water bottle and drink earlier in the experiment than rats in the group INEE that were possibly less active. As drinking would occur in temporal proximity to the delivery of the reinforcer, the probability of its occurrence would increase (Killeen and Pellón, 2013). In addition, Catania (1971) proposed that, the higher the rate of the behavior carried out before the reinforcer delivery, the higher the levels of the behavior will be reinforced. Therefore, it makes sense that if rats with EE were more active than those with INEE, they would develop higher levels of drinking. Jones et al. (1989) reported increased activity in the isolation-reared group, but they measured activity in the back of the chamber, i.e., far from the feeder and the licking spout. This may suggest that EE does not increase exploratory activity in other areas that the one dealing with the behaviors in course, but rather enhances learning ability of the task, leading the animals to spend more time near the water bottle, thereby explaining the reduced overall activity in the back of the chamber showed by subjects with access to EE in Jones et al. (1989) study.

Incidentally, neither the present results, nor those of Jones et al. (1989), are easily accommodated into a framework that explains SID and other induced behaviors to be a coping strategy to deal with aversive situations (Papini and Dudley, 1997; Thomka and Rosellini, 1975), in this case, the period after food delivery. If this were the case, the opposite results should be obtained, as SID would be favored by conditions that further amplify the stressful situation. The absence of an effect of EE on plasma corticosterone levels, as reported by Jones et al. (1989), and results reported by Rick et al. (2018) who failed to replicate Thomka and Rosellini's (1975) study, speaks in the same direction. However, the change from living in groups in the home cages to being tested in isolation in the conditioning chambers might have also elevated activation in EE rats via a higher stressful experience than that of the INEE rats that stayed all time in isolation. This possibility, even possible during the initial sessions of the experiment, seems unlikely to have persisted for as many as 25 sessions.

Regarding the second aim of the present study, it seems that EE accelerates learning at least in this type of task, which could be beneficial for some experimental preparations. However, it is important to note that a greater amount of behavior can be counterproductive in other behavioral tasks, for example, in the area of self-control, as excessive behavior can lead to impulsive choices (Íbias and Pellón, 2011; Ramos et al., 2019; Wang et al., 2017), or to poor performance in tasks that require control of the motor response, such as differential reinforcement of low rates schedules (Orduña et al., 2009), so further research regarding the increase of general activity as a result of EE should be carried out.

Recent studies have provided valuable insights into the sex-dependent effects of environmental enrichment (EE) on behavior. Gender differences were observed in social exploratory patterns, with enriched males displaying heightened exploratory behavior towards other rats compared to control males, while no significant differences were found among females (Peña et al., 2006). Social enrichment primarily improves performance, specifically habituation, in both males and females, but the effects of enrichment, whether physical or social, appear to be more pronounced in males, particularly indicated by decreased activity over time in the open field, suggesting enhanced information processing (Elliott and Grunberg, 2005). Moreover, following traumatic brain injury, EE resulted in improved spatial memory performance specifically in males, while no significant enhancement was observed in females (Gupte et al., 2019; Wagner et al., 2002). These findings highlight the importance of considering sex as a critical factor in studying the effects of environmental enrichment on behavior, with implications for tailored approaches to optimize behavioral outcomes in both males and females.

To conclude, the results of the present experiment indicate that EE accelerates the acquisition of SID, without affecting its temporal distribution. Therefore, the implementation of EE protocols indicated by Directive 2010/63/EU of the European Parliament (European Medicines Agency, 2010) should be carried out without interfering with obtaining valid results consistent with previous studies in this area.

Declaration of Competing Interest

The authors declare no conflict of interest to disclose.

Data availability

Data can be retrieved from: https://osf.io/b29y3/.

Acknowledgements

The conduct of the experimental work and the preparation of manuscript were funded by grant PSI2016-80082-P (Ricardo Pellón: Principal Investigator) from the Spanish Government (Ministerio de Economía y Competitividad, Secretaría de Estado de Investigación, Desarrollo e Innovación). Esmeralda Fuentes-Verdugo was awarded by the Spanish Government (Ministerio de Universidades) with a FPU scholarship (FPU15/03799) part of the Spanish program for professional training of university lecturers. Gabriela E. López-Tolsa was awarded a Scholarship to undertake PhD-level studies abroad (255325/383739) by the Mexican Government (Consejo Nacional de Ciencia y Tecnología). We thank Antonio Rey for excellent technical support and Felizdania Hernández for her help in data collection.

Appendix A

Table A1
Individual estimated parameters and transition points.

	Sessions 1–5				Sessions 6–10				Sessions 11–15				Sessions 16–20				Sessions 21–25			
	Peak	Width	R^2	Trans	Peak	Width	R^2	Trans	Peak	Width	R^2	Trans	Peak	Width	R^2	Trans	Peak	Width	R^2	Trans
EE1	5.48	11.79	0.91	15	4.38	10.23	0.96	21.8	4.12	9.20	0.95	20	3.77	8.59	0.95	19.4	4.47	9.53	0.94	20.6
EE2	4.71	12.69	0.95	15	3.68	11.07	0.97	18.2	3.47	9.82	0.97	16.2	3.48	10.49	0.97	14.8	3.81	10.36	0.97	16.2
EE3	3.81	10.92	0.94	15.6	4.00	10.14	0.96	20	5.73	11.17	0.90	21	5.27	9.40	0.82	23.4	7.67	9.78	0.49	27.4
EE4	3.36	8.84	0.90	16	2.41	8.03	0.97	14.8	2.07	7.04	0.98	14.2	1.94	7.22	0.97	14.6	2.16	6.77	0.93	13.4
EE5	3.52	10.47	0.92	11.8	3.92	9.37	0.94	19.2	4.10	9.53	0.93	20.4	3.19	8.03	0.94	19.8	3.17	7.69	0.92	21.6
EE6	7.05	13.37	0.89	24.2	5.53	11.90	0.95	25.4	6.16	11.37	0.92	24.2	5.56	10.98	0.93	24	5.14	9.86	0.93	23.2
EE7	5.47	12.28	0.88	12	4.87	10.57	0.93	23.4	4.13	8.93	0.96	22	4.11	8.34	0.94	20.2	4.03	8.05	0.94	18.4
EE8	4.50	9.55	0.92	15.4	4.86	8.02	0.87	19.6	5.00	8.30	0.90	20.8	5.02	8.30	0.89	21.6	5.34	7.86	0.82	19.6
EE9	4.77	9.99	0.93	17.8	4.21	9.14	0.96	19.2	5.20	9.77	0.93	22	4.09	8.25	0.94	19.6	3.82	8.02	0.95	18.8
EE10	4.66	11.75	0.96	15.2	4.25	12.39	0.97	18.8	3.76	11.38	0.99	18.8	3.40	10.26	0.99	17	2.97	8.97	0.99	15.6
EE11	3.34	11.46	0.93	13	3.56	11.25	0.97	18.2	3.56	10.47	0.97	18	3.26	9.82	0.97	18	3.84	10.09	0.96	18.2
EE12	4.97	11.52	0.90	13.2	3.56	10.58	0.99	18.4	3.66	9.20	0.96	20	3.55	9.01	0.97	18.8	4.11	9.97	0.95	20
INEE1	9.89	17.28	0.75	10.2	5.92	13.63	0.95	19.8	4.62	11.60	0.96	23.2	4.54	10.64	0.95	24.6	4.17	9.66	0.95	22.2
INEE2	5.22	12.20	0.91	14.4	4.40	9.96	0.95	19.6	4.42	10.49	0.97	20	3.94	9.99	0.98	18.6	3.66	9.31	0.97	17.8
INEE3	n/c	n/c	n/c	10	n/c	n/c	n/c	10	3.56	11.25	0.98	16.6	3.23	10.02	0.97	16.6	2.96	9.28	0.97	15.8
INEE4	4.03	10.82	0.95	18.8	3.64	9.91	0.97	20	3.31	9.40	0.98	19	3.09	9.20	0.98	16.8	3.04	8.76	0.97	16.8
INEE5	7.08	13.85	0.87	17	4.03	9.83	0.95	19	2.72	8.32	0.97	16.4	2.35	7.94	0.99	15.4	2.20	7.18	0.98	13
INEE6	n/c	n/c	n/c	10	4.69	12.24	0.97	13.2	4.09	11.32	0.97	18	3.66	10.04	0.96	16.4	4.35	10.20	0.90	18
INEE7	7.45	17.44	0.81	11	3.92	11.76	0.95	17.2	3.89	11.42	0.97	17.4	4.27	11.05	0.95	19.6	4.42	10.79	0.95	20.4
INEE8	10.00	13.06	0.52	11	3.97	10.86	0.96	15.8	3.91	10.91	0.95	18.6	3.07	9.63	0.98	16.8	2.95	8.07	0.94	15.6
INEE9	n/c	n/c	n/c	10.8	3.18	8.61	0.97	14	2.99	7.20	0.95	15.4	2.85	6.87	0.95	15.2	3.09	7.61	0.96	15.8
INEE10	4.19	12.81	0.94	12.8	3.73	11.28	0.98	19.4	4.00	11.07	0.97	19	4.04	10.30	0.95	20.2	4.06	10.39	0.93	21.6
INEE11	5.38	13.49	0.93	12	4.44	11.59	0.97	19.6	3.12	9.40	0.98	17.4	2.79	8.61	0.99	17.2	2.97	8.55	0.98	16.8
INEE12	4.49	9.56	0.80	12.2	4.06	10.75	0.97	15.8	2.33	6.57	0.97	13.8	2.47	6.42	0.97	13.6	2.72	6.84	0.96	14

Note. Peak and width refer to the estimated mean and standard deviation, respectively, derived from the Gaussian normal distribution fitted to the individual data. n/c = the model did not converge for that session/subject. R^2 is the coefficient of determination. Trans = time of transition.

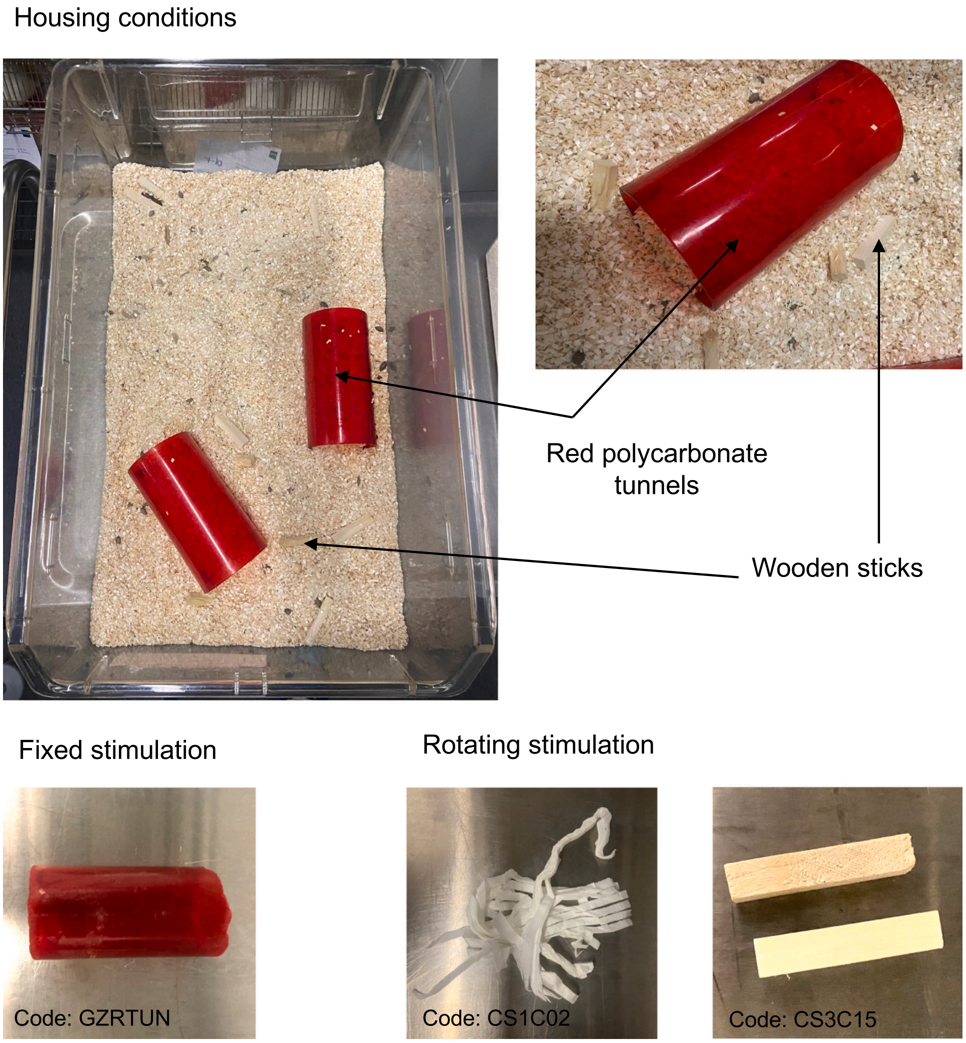

Fig. A1. Photos of the toys used in the environmental-enrichment protocol. Note. Fixed stimulation: was always present. Rotating stimulation was changed on Mondays (wooden sticks) and Fridays (paper). All products were acquired from Sodispan. Codes represent products from the Sodispan catalogue (www.sodispan.com).

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