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Dissociating the Roles of Dorsal and Ventral CA1 for the Temporal Processing of Spatial Locations, Visual Objects, and Odors

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The differential contributions of the dorsal and ventral hippocampus for learning and memory have long been of interest. The present experiments were designed to evaluate the contributions of dorsal CA1 and ventral CA1 for temporal processing. Animals were run on three temporal ordering paradigms: one with visual objects, one with olfactory stimuli, and one with spatial locations. Animals with lesions to dorsal CA1 showed deficits for the temporal ordering of visual objects relative to control animals, and deficits for the temporal ordering of spatial locations relative to control and ventral CA1 lesioned animals. Animals with lesions to ventral CA1 showed deficits for the temporal ordering of olfactory information relative to control and dorsal CA1 lesioned animals, and a mild deficit for the temporal ordering of visual objects relative to control animals, but not as severe as those shown by the dorsal CA1 lesioned animals. These data suggest that dorsal CA1 and ventral CA1 contribute to temporal ordering processes, and that dorsal CA1 and ventral CA1 are dissociable for temporal ordering based upon the nature of the information that is processed.

Keywords: dorsal CA1, ventral CA1, temporal processing, episodic memory, temporal context

There has been a recent surge in research concerning the differential roles of the dorsal and ventral portions of the hippocampus. The hypothesis tested by this research is based on differences in intrinsic and extrinsic connectivity along the dorsal-ventral axis of the hippocampus (cf. Amaral & Witter, 1989; Risold & Swanson, 1996). Theories encompassing ventral hippocampal function include a role in mediating anxiety (Bannerman et al., 2004), hyponeophagia (Bannerman et al., 2002), retrieval of contextual and stimulus-specific information during trace and delay fear conditioning (cf. Rogers, Hunsaker, & Kesner, 2006; Rudy & Matus-Amat, 2005; Yoon & Otto, 2007), and behavioral inhibition (cf. Gray & McNaughton, 1983, 2001; McDonald, Jones, Richards, & Hong, 2006). The dorsal hippocampus has been proposed as the neurological substrate underlying spatiotemporal processing (O'Keefe & Nadel, 1978; Rolls & Kesner, 2006). On the basis of this hypothesis, numerous reports have effectively dissociated the dorsal and ventral halves of the hippocampus across spatial and nonspatial domains (Bannerman et al., 1999, 2002, 2004; Moser & Moser, 1998). Despite the aforementioned dissociations, an alternative hypothesis suggests that the ventral hippocampus may support spatial memory and may assist in performance of spatial and nonspatial tasks primarily dependent upon the dorsal hippocampus if the animal is trained properly (de Hoz, Knox, & Morris, 2003; McDonald et al., 2006). It has also been proposed that the dorsal and ventral hippocampus participate in similar processing of information (Rudy & Matus-Amat, 2005).

To date, no tasks have evaluated the role of ventral CA1 for temporal processing outside of fear conditioning (cf. Rogers et al., 2006) and trace associative learning (Kesner, Hunsaker, & Gilbert, 2005). The present study was designed to evaluate the differential roles for dorsal CA1 and ventral CA1 for processing information pertaining to the temporal order of visual objects, olfactory stimuli, and spatial locations. The data reveal that dorsal CA1, but not ventral CA1, mediates temporal ordering for spatial locations; ventral CA1, but not dorsal CA1, mediates temporal ordering for olfactory information; and both dorsal and ventral CA1 mediate temporal ordering for visual objects, although dorsal CA1 seems to be more important than ventral CA1.

Materials and Method

Animals

Seventeen Long-Evans rats (Simonsen Laboratories, Inc., Gilroy, CA), approximately 4 months of age and weighing 300–400 g at the start of experimentation, served as subjects. The rats were housed individually in plastic tubs located in a colony with a 12-hr light–dark cycle. All testing was conducted during the light portion of the light–dark cycle. All rats were free fed and had ad libitum access to water. The rats were not food deprived during experimentation. All experiments were conducted according to the National Institutes of Health (1986) "Guide for the Care and Use of Laboratory Animals" and the University of Utah Institutional Animal Care and Use Committee.

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Surgical Methods

The surgical method was identical to that reported by Rogers et al. (2006). Experimentally naive rats were randomly assigned to a surgery group (ventral CA1, $n = 5$; dorsal CA1, $n = 6$; control, $n = 6$). Rats were anesthetized and maintained with isoflurane (2%–4% [vol/vol] in 2 L/min medical air) and given atropine sulfate (0.2 mg/kg im) as a prophylactic. Rats that received a lesion of the ventral CA1 subregion were given 0.75 ml of diazepam (2 mg/ml ip) 10 min prior to surgery to prevent any seizure activity that may result from the excitotoxic lesions of ventral CA1. Rats were placed in a stereotaxic apparatus (David Kopf Instruments, Tunjana, CA) and the scalp was incised and retracted to expose bregma and lambda, which were adjusted into the same horizontal plane by moving the incisor bar dorsoventrally. Excitotoxic lesions were made using ibotenic acid (Ascent Scientific, Bristol, UK; 6 mg/ml PBS), infused using a microinfusion pump (Cole-Parmer, Vernon Hills, IL) and a 10-μl Hamilton syringe (Hamilton, Reno, NV) at a rate of 6 μl/hr and a volume of 0.10 or 0.15 μl depending on the site, bilaterally into three sites. After infusion, the injection cannula remained in each site for 1 min to allow diffusion of the injected excitotoxin. The distinction between dorsal and ventral hippocampus were defined after Moser and Moser (1998) and Bannerman et al. (2002) as the midpoint of the hippocampus. The coordinates for dorsal CA1 lesions ($n = 6$), based on the Paxinos and Watson (1997) atlas, were (a) 3.6 mm posterior to bregma, 1.0 mm lateral to the midline, 2.4 mm ventral to dura (0.1 μl of ibotenic acid injected); (b) 3.6 mm posterior to bregma, 2.0 mm lateral to the midline, 2.1 mm ventral to dura (0.1 μl); and (c) 3.6 mm posterior to bregma, 3.0 mm lateral to the midline, 2.3 mm ventral to dura (0.15 μl). Ventral CA1 lesions ($n = 5$) were also made using ibotenic acid, infused following the same procedures as dorsal CA1 lesions, into three sites within the ventral hippocampus located (a) 5.3 mm posterior to bregma, 3.0 mm lateral to the midline, 2.8 mm ventral to dura (0.1 μl of ibotenic acid injected); (b) 5.3 mm posterior to bregma, 5.2 mm lateral to the midline, 4.0 mm ventral to dura (0.1 μl); and (c) 5.3 mm posterior to bregma, 5.8 mm lateral to the midline, 6.2 mm ventral to dura (0.15 μl). Vehicle control lesions (ventral CA1 vehicle, $n = 3$; dorsal CA1 vehicle, $n = 3$) were made using the same coordinates and procedures; however, equivalent volumes of PBS vehicle were infused instead of ibotenic acid. Following surgery, the incision was sutured, 1.5 ml of PBS was injected into each hip subcutaneously to expel the anesthetic, and the rats were allowed to recover on a heating pad before returning to their home cage. In addition, rats received acetaminophen (Children's Tylenol, Johnson & Johnson, Inc., Fort Washington, PA; 200 mg/100 ml water) in their drinking water as an analgesic and were provided with powdered food for 3 days following surgery. All the rats were monitored for epileptiform induced behavioral changes for 7 days postsurgery: none was observed.

Behavioral Methods

Each rat was run on each of three tasks that measured temporal processing of olfactory information, spatial locations, and visual objects. The order was randomized for each rat, and all tests were videotaped for later analysis by a blinded experimenter. In all cases, each rat received the temporal order test first, followed by the novelty test 2 days later for the same element (e.g., odor, spatial location, or object). The rat then received a different temporal order task 1 week after that. All of the odors, objects, and spatial locations were randomized such that, for example, any given odor could be the first, second, third, or the novel odor for any given rat. This randomization was to ensure the validity of the results.

Temporal order and novelty detection for odors. Prior to experimentation, 10 odors were chosen and set into groups for use during the experimentation. These odors were mixed with playground sand and placed into identical cups that were 3.5 cm in height and 5 cm in width. Odors were chosen to be as distinct as possible and not from the same family of odors (e.g., garlic and onion powders were not used concurrently due to olfactory similarity, and no allopathic odors were used). To habituate the rats to the box prior to presenting the odors, each rat was placed in the box for 10 min the day preceding experimentation before the presentation of the olfactory stimuli.

For temporal ordering of olfactory information, the rats were tested on a modification of the paradigms described in Hannesson, Howland, and Phillips (2004); Mitchell and Laiacona (1998); and Hoge and Kesner (2007; cf. Figure 1A). Each rat was placed in the box with two copies of the same odor present on different sides of the box and was allowed to explore this first odor for 5 min. This exploration was followed by a 3-min intersession interval during which the rat was placed in a cage. The rat was placed back in the box with two copies of a second odor and was allowed 5 min to explore. After another 3-min intersession interval, the rat was placed in the box with two identical copies of a third odor and allowed to explore for 5 min. After a 10-min intersession interval

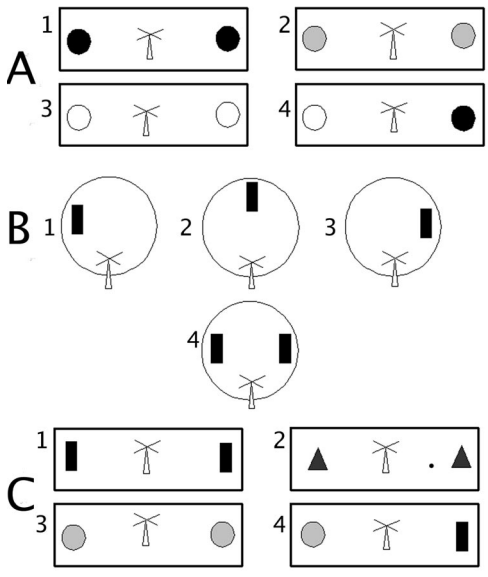

Figure 1. Behavioral paradigms. (A) Temporal order for olfactory information. The black, grey, and white circles represent distinct odors. (B) Temporal order for spatial locations. The objects used in each session are identical so the spatial location information is all that differs. (C) Temporal order for visual objects. Each shape represents a different object. 1, 2, 3, and 4 refer to the session number.

to allow for sufficient consolidation of the odors presented, the rat was placed in the box with a copy of the first odor and a copy of the third odor and allowed to explore for 5 min for the test. Left and right placement of the first and last odors during the test was pseudorandomized.

As a control for the temporal ordering task, a novelty detection for olfactory information task was given 48 hr after the temporal ordering task; the previous study phase protocol was followed, but the test phase was modified. All sessions and intersession intervals were the same length as they were during the temporal order task. For the novelty test, the rat was presented with the first odor presented that day and a novel odor to which the rat had not been previously exposed and was allowed 5 min to explore. This tested the rat's preference for a novel odor over a familiar odor.

Temporal order and novelty detection for spatial locations. The temporal order and novelty detection for spatial locations task was run on an a modified open field cheeseboard covered with a thick vinyl sheet to obscure the holes (cf. Hunsaker, Mooy, Swift, & Kesner, 2007; Lee, Hunsaker, & Kesner, 2005). Three identical objects were prepared. These objects were large transparent carafes (30 cm in height and 10 cm in width) with rainbow-colored party streamers placed in the bottom to provide a contrast with the distal environment. These objects were designed to be large and attract the attention of the rat but transparent to allow the rat to see the distal environment when close to the object. Seven spatial locations were defined on the maze by marking their locations on a TV monitor in the adjacent room. This allowed the experimenter to use the precise spatial locations intended.

One day prior to experimentation, the rats were placed on the open field with no objects present to habituate to the open field and to explore the spatial layout of the room. This was intended to allow the rats to learn the spatial layout of the room and to habituate to the board prior to experimentation.

For the temporal ordering of spatial locations task, each rat was placed on the maze facing due east with an object in a particular spatial location and was allowed to explore for 5 min (cf. Figure 1B). After this initial exploration, the rat was removed to a cage outside the running room for a 3-min intersession interval. After this interval, the rat was placed on the maze again with the object moved to a second spatial location. The rat was given 5 min to explore. After another 3-min intersession interval, the rat was placed on the maze with the object moved to a third spatial location and was allowed to explore for 5 min. Following a 30-min intersession interval to allow for sufficient consolidation of the spatial information acquired during the study phase, the rat was placed on the maze with identical objects in the first and last spatial locations experienced and was allowed to explore for 5 min.

As a control for the temporal ordering task, a novelty detection for spatial locations task was given 48 hr later, only the test phase differed from the temporal ordering task. All sessions and intersession intervals were the same length as they were during the temporal order task. During the test, the two identical objects covered the first spatial location experienced and a novel spatial location never before occupied by the object. The rat explored for 5 min. This tested the rat's preference for a novel spatial location over a familiar spatial location.

Temporal order and novelty detection for visual objects. For this experiment, a box (79 cm in length, 33 cm in width, and 41 cm in height) was constructed out of translucent red Plexiglas. The floor of the box was made of wood and was painted white. A small round sticker was placed on the floor of the box on each side centered in the width of the box and 5 cm from the edge of the box. This was to assist the experimenter in placing the visual object in the same location every time and to eliminate unintentional spatial cues. Prior to experimentation, 10 distinct visual objects were chosen and set into groups for use during the experimentation. These objects ranged from 5.5 to 8.0 cm in height and from 2.0 to 5.5 cm in width. The objects were made of solid plastic, metal, or painted wood.

To habituate the rats to the box prior to presenting the objects, each rat was placed in the box for 10 min the day preceding experimentation. This allowed the rats to explore the environment selectively and to later selectively explore the visual objects during the experiment instead of focusing their exploration on the box.

To evaluate the relative contributions of dorsal CA1 and ventral CA1 for temporal ordering of visual object exploration, rats were tested on a modification of the paradigms presented in Hannesson et al. (2004), Mitchell and Laiacona (1998), and Hoge and Kesner (2007;cf. Figure 1C). Each rat was placed in the box with two copies of the same visual object present on both sides of the box and was allowed to explore these first objects for 5 min. This exploration was followed by a 3-min intersession interval during which the rat was placed in a cage. The rat was then placed in the box with two copies of a second object and allowed 5 min to explore. After another 3-min intersession interval, the rat was placed in the box with two identical copies of a third object and allowed to explore for 5 min. After a 10-min intersession interval to allow for sufficient consolidation of the odors presented, the rat was placed in the box with a copy of the first object and a copy of the third object and given 5 min to explore for the test. Left and right placement of the first and third visual objects during the test phase was pseudorandomized.

As a control for the temporal ordering task, a novelty detection for visual objects task was given 48 hr after the temporal ordering for visual objects task; the study phases were carried out similarly and the test phase was modified. All sessions and intersession intervals were the same length as they were during the temporal order task. For the novelty test, the rat was presented with the first object and a novel object to which the rat had not been given any previous exposure and was allowed 5 min to explore. This tested the rat's preference for a novel visual object over a familiar visual object.

Data collection and statistical analysis. In all experiments, object exploration was the dependent variable and was recorded by an experimenter blind to the experimental manipulations of each rat from videotapes. Exploration totals were used to calculate a ratio score to normalize for total exploration time. The ratio was calculated as follows. For temporal order tasks, the time spent in seconds exploring the object, odor, or spatial location that came later in the sequence was subtracted from the time spent exploring the object, odor, or spatial location that came earlier in the sequence. This was divided by the total exploration time of the two objects, odors, or spatial locations (e.g., [(earlier – later)/(earlier + later)]). This ratio was designed such that a score of zero indicated that there was no preferential reexploration of one element over the otherand visual interpretation of the plotted data was faciliated because a positive number indicates that the rat explored the first object, odor, or spatial location presented over the last. For the

novelty detection paradigm, the ratio was the time spent exploring the familiar object, odor, or spatial location subtracted from the time spent exploring the novel object, odor, or spatial location and then divided by the total exploration time in seconds of the two objects, odors, or spatial locations (e.g., [(novel – familiar)/(novel + familiar)]). A positive result of this calculation means that the rat explored the novel visual object, odor, or spatial location more than the familiar one presented during the study phase. To validate the analysis, the ratio scores for the control group ($n = 6$) were compared to the null hypothesis of no preference (e.g., the ratio score = 0). A nonzero ratio reflects a preference for one object over the other. Only when the *t* test showed that control rats showed a significant preference for one object over the other (e.g., a $p < .05$ result of the *t* test) were further analyses performed. After the analyses of variance (ANOVAs), further *t* tests were performed for rats in groups that appeared to show the opposite preference from that shown by control rats.

These ratio scores were calculated and input into a MATLAB matrix (statistics toolbox on MATLAB Version 6.5 R13; Natick, MA) that was used to calculate the one-way ANOVA with lesion group (control, dorsal CA1, and ventral CA1) as the grouping factor. Tukey's honestly significant difference (HSD) post hoc paired comparison tests were run on all significant effects, and results were considered significant at $p < .05$.

Locomotor activity was also monitored to control for differences in locomotor activity. For the visual object and olfactory temporal ordering tasks, every time the rat crossed the midline of the box it was recorded and the number of midline crossings was used to assess locomotor activity. For the spatial locations temporal ordering task, a 3×3 grid was drawn on the monitor and every time a rat crossed a grid it was recorded (cf. Hunsaker et al., 2007).

Histological Methods

After all behavioral testing was completed, rats were killed with a lethal dose of sodium pentobarbital (70 mg/ml ip) and perfused intracardially with 0.9% PBS (pH 6.0) for 2 min followed by 10% (wt/vol) formalin (pH 7.0) for another 5 min. The brains were then extracted and stored in 30% (wt/vol) sucrose formalin at 4 °C for 72 hr before being frozen and sliced into 40-μm sections with a freezing-stage microtome. Half of the control brains and all of the dorsal CA1 lesioned brains were cut along the coronal plane, whereas all of the ventral CA1 lesioned brains and the other half of the control brains were cut along the transverse plane. In both cases, every third section from the tissue block containing the hippocampus was mounted on microscopic slides and Nissl stained with cresyl violet for microscopic verification of the lesions. Sections were photographed and imported into ImageJ (v1.35j; National Institutes of Health, Bethesda, MD) for quantitative lesion analysis. Briefly, the anatomical region in question (dorsal CA1 or ventral CA1) was traced using the freehand selection tool on ImageJ, and the area contained within the tracing was calculated. The spared portion of the anatomical region was then traced and the percent damage was calculated based upon those two values. Dentate gyrus and CA3 (both dorsal and ventral) were also traced to evaluate nonspecific damage. The percent damage for each rat was calculated from the sections and then averaged across rats.

Results

Histological Results

No rats were excluded from statistical analysis due to inaccurate surgery. Figure 2 shows representative sections for control, dorsal CA1 lesioned, and ventral CA1 lesioned rats. Dorsal CA1 lesioned rats had (mean ± *SE*) 84 ± 5.2% damage to the pyramidal cell layers of CA1 with 4.5 ± 0.9% damage to the underlying medial blade of the dentate gyrus and 8.8 ± 2.1% damage to CA3a,b pyramids. Ventral CA1 lesioned animals had 72.4 ± 8.3% damage to the ventral CA1 pyramidal cell layer with 1.5 ± 0.25% damage to the ventral dentate gyrus and 12.5 ± 4.6% damage to the ventral CA3a,b pyramidal cell layer. In no cases was extrahippocampal damage to the parietal, entorhinal, or perirhinal cortices observed. There was no damage beyond that caused by the cannula track in both dorsal and ventral vehicle control lesioned rats. In no cases was there parietal, perirhinal, postrhinal, or entorhinal cortex damage observed.

Behavioral Results

Figure 3 shows the results for the temporal ordering (Figure 3A) and novelty detection (Figure 3B) for visual object, odors, and spatial locations. During all tasks, locomotor activity did not differ among groups (all *p*s > .2; data not shown). There also were no differences between odor, spatial location, or object exploration as

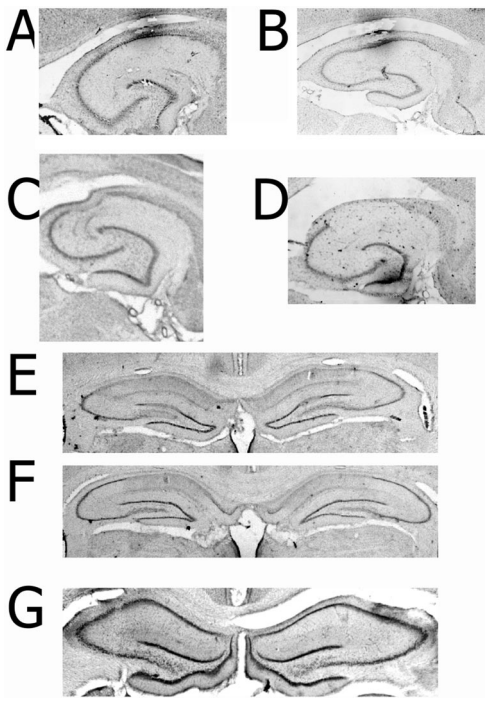

Figure 2. Histology. (A-B) Control sections from different rats showing the ventral hippocampus in a horizontal section. (C-D) Representative ventral CA1 lesions from different rats showing selective ventral CA1 damage using horizontal sections. (E-F) Representative sections from different rats showing selective dorsal CA1 damage using coronal sections. (G) Representative section from a control rat using coronal sections.

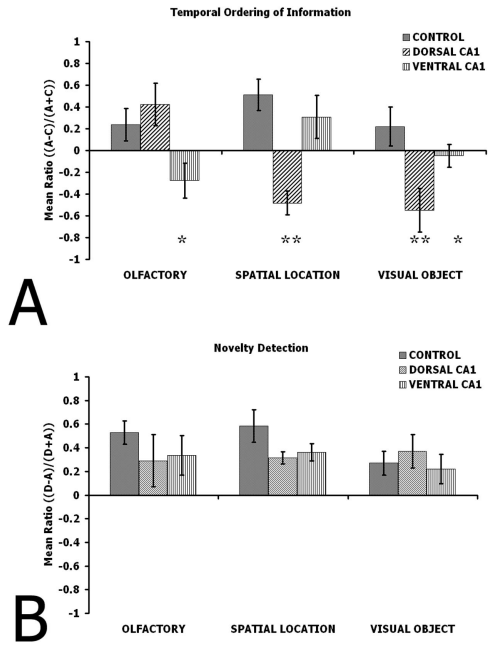

Figure 3. Behavioral results. (A) Temporal ordering for olfactory, spatial, and visual object information. For olfactory information, notice that only ventral CA1 shows a deficit. For spatial locations, notice that only dorsal CA1 shows a deficit. For visual objects, notice that both dorsal CA1 and ventral CA1 show a deficit, but dorsal CA1 shows a much larger deficit than ventral CA1. (B) Novelty detection for olfactory, spatial, and visual object information. Note that there were no differences between groups. $^{*}p < .05$. $^{**}p < .01$.

a function of session (e.g., the rats explored the first odor as much as the second and third presented; all *p*s >0.1; cf. Table 1).

Temporal Order and Novelty Detection for Odors

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the odors over the other during the test phase. If the rats show a preference for one odor over another, the ratio score will be significantly above or below zero. The data reveal that the control rats did in fact show a significant preference for the first odor over the last one presented during the study phase reflecting a nonzero ratio score, $t(5) = 2.49$, $p < .03$. The ratio scores calculated for dorsal CA1 lesioned, ventral CA1 lesioned, and control rats were compared with a one-way ANOVA with lesion as the between factor. There was a significant effect for lesion, $F(2, 16) = 7.18$, $p = .007$. A subsequent Tukey's HSD post hoc paired comparisons test revealed that control rats and dorsal CA1 lesioned rats did not significantly differ ($p > .05$). Both control rats and dorsal CA1 lesioned rats explored the first odor presented during the test more than ventral CA1 lesioned rats ($p < .05$). The ventral CA1 lesioned rats showed a significant preference for the odor presented last in the sequence, $t(4) = 1.42$, $p < .01$.

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the odors over the other during the test phase. The data reveal that the rats in the control group did in fact show a significant preference for the novel odor over the one presented during the study phase reflecting a nonzero ratio score, $t(5) = 3.22$, $p < .01$ For novelty detection for odors, the ratios were again compared with a one-way ANOVA. There was no effect for lesion, $F(2, 16) = 1.1$, $p = .36$.

Temporal Order and Novelty Detection for Spatial Locations

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the spatial locations over the other during the test phase. The data reveal that the rats in the control group did in fact show a significant preference for the first spatial location over the last spatial location presented during the study phase reflecting a nonzero ratio score, $t(5) = 2.13$, $p < .04$. The ratio scores calculated for dorsal CA1 lesioned, ventral CA1 lesioned, and control rats were compared with a one-way ANOVA with lesion as the between factor. There was a significant lesion effect, $F(2, 16) = 12.8$, $p = .0009$. A subsequent Tukey's HSD post hoc paired comparisons test revealed that control rats and ventral CA1 lesioned rats did not significantly differ ($p > .05$). Both control rats and ventral CA1 lesioned rats explored the first spatial location presented during the test more than dorsal CA1 ($p < .01$). The dorsal CA1 lesioned rats showed a significant preference for the spatial location presented last in the sequence, $t(5) = 2.38$, $p < .01$.

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the spatial locations over the other during the test phase. The data reveal that the rats in the control group did in fact show a significant preference for the novel spatial location over the one presented during the study phase reflecting a nonzero ratio score, $t(5) = 2.37$, $p < .03$. For the novelty detection for spatial locations task, the ratios were again compared with a one-way ANOVA. There was no effect for lesion, $F(2, 16) = 2.78$, $p = .097$.

Temporal Order and Novelty Detection for Visual Objects

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the objects over the other during the test phase. The data reveal that the rats in the control group did in fact show a significant preference for the first object over the last object presented during the study phase reflecting a nonzero ratio score, $t(5) = 2.62$, $p < .02$ The ratio scores calculated for dorsal CA1 lesioned, ventral CA1 lesioned, and control rats were compared with a one-way ANOVA with lesion as the between factor. There was a significant lesion effect, $F(2, 16) = 13.38$, $p = .0006$. A Tukey's HSD post hoc paired comparisons test revealed that control rats explored the first object presented during the test more than ventral CA1 ($p = .05$) and more than dorsal CA1 ($p < .01$) lesioned rats. Ventral CA1 rats explored the first object more than dorsal CA1 ($p < .05$), suggesting a graded involvement of the dorsal and ventral halves of CA1, with a more critical involvement of dorsal CA1. Only dorsal CA1 lesioned rats showed a significant preference for the object presented last in the sequence: dorsal CA1, $t(5) = 2.19$, $p < .01$; ventral CA1, $t(4) = -1.02$, $p > .05$.

Ratio scores for the control group were analyzed to verify that, as a group, the rats showed a significant preference for one of the objects over the other during the test phase. The data reveal that the

Table 1
Mean Values ± Standard Errors for Exploration and Grid Crossings (X-ing) During the Temporal Ordering and Novelty Detection Tasks

		Session					
		First		Second		Third	
Task	Lesion	Exploration	Grid X-ing	Exploration	Grid X-ing	Exploration	Grid X-ing
Temporal order odor							
	Control	6 ± 2	11 ± 4	5 ± 3	9 ± 3	5 ± 2	14 ± 2
	Dorsal CA1	9 ± 2	13 ± 3	4 ± 2	11 ± 2	7 ± 1	13 ± 5
	Ventral CA1	5 ± 3	9 ± 5	8 ± 3	14 ± 4	6 ± 3	16 ± 3
Spatial location							
	Control	14 ± 5	38 ± 6	11 ± 3	25 ± 4	13 ± 4	19 ± 3
	Dorsal CA1	17 ± 3	40 ± 5	10 ± 2	22 ± 4	11 ± 2	17 ± 6
	Ventral CA1	15 ± 2	34 ± 5	13 ± 2	28 ± 3	12 ± 3	21 ± 5
Visual object							
	Control	8 ± 3	10 ± 3	7 ± 2	8 ± 3	8 ± 2	9 ± 3
	Dorsal CA1	8 ± 2	8 ± 4	8 ± 3	5 ± 4	9±1	5 ± 3
	Ventral CA1	9 ± 2	9 ± 4	8 ± 3	7 ± 2	6 ± 3	7 ± 3
Novelty detection odor							
	Control	7 ± 3	19 ± 6	6 ± 1	16 ± 3	6 ± 2	12 ± 3
	Dorsal CA1	4 ± 2	23 ± 5	8 ± 2	18 ± 4	5 ± 2	15 ± 4
	Ventral CA1	8 ± 2	17 ± 5	3 ± 1	14 ± 4	9 ± 2	11 ± 2
Spatial location							
	Control	21 ± 4	46 ± 8	17 ± 2	32 ± 12	12 ± 2	23 ± 10
	Dorsal CA1	15 ± 5	51 ± 12	12 ± 3	43 ± 8	19 ± 6	26 ± 8
	Ventral CA1	18 ± 4	49 ± 11	16 ± 5	36 ± 14	14 ± 3	20 ± 6
Visual object							
	Control	6 ± 1	13 ± 3	7 ± 2	10 ± 4	5 ± 2	9 ± 3
	Dorsal CA1	4 ± 2	11 ± 4	6 ± 2	12 ± 3	7 ± 1	10 ± 3
	Ventral CA1	8 ± 2	14 ± 4	6 ± 1	13 ± 4	8 ± 1	15 ± 2

control group did in fact show a significant preference for the novel object over the one presented during the study phase reflecting a nonzero ratio score, $t(5) = 3.48$, $p < .01$ For novelty detection for visual objects, the ratios were again compared with a one-way ANOVA. There was no lesion effect, $F(2, 16) = 2.72$, $p = .10$.

Discussion

Temporal Order for Olfactory Stimuli

The data suggest that ventral CA1 is capable of processing olfactory information into a temporal code that can be recalled, whereas dorsal CA1 is not critically involved for this processing. This report supports previous anatomical models suggesting that the dorsolateral band of the entorhinal cortex, which carries olfactory information from olfactory and perirhinal cortices, projects to the ventral hippocampus more robustly than to the dorsal hippocampus (Furtak, Wei, Agster, & Burwell, 2007; Kerr, Agster, Furtak, & Burwell, 2007; Steffenach, Witter, Moser, & Moser, 2005; Witter, Wouterlood, Naber, & van Haeften, 2000). Furthermore, these data reveal a dissociation between dorsal CA1 and ventral CA1 for temporal ordering of olfactory information. Ventral CA1, but not dorsal CA1, mediates the temporal ordering of olfactory information.

Temporal Order for Spatial Locations

The data suggest that dorsal CA1 subserves the temporal ordering of spatial information and that ventral CA1 does not provide a meaningful contribution. These data suggest that ventral CA1 does not receive highly processed spatial information to be temporally processed (cf. Furtak et al., 2007; Kerr et al., 2007). These data provide a dissociation between dorsal CA1 and ventral CA1 for the temporal processing of spatial information, wherein dorsal CA1, but not ventral CA1, mediates spatial information processing.

Temporal Order for Visual Objects

The present results suggest that both dorsal CA1 and ventral CA1 subserve temporal processing of visual information. From the present data, however, it appears that dorsal CA1 plays a more important role than ventral CA1 for the processing of visual information. These data are novel in that they demonstrate that ventral CA1 is capable of processing visual information within a temporal framework. These data support previous reports of ventral hippocampal involvement in retrieval of contextual and elemental fear (Maren & Holt, 2004; Rogers et al., 2006; Rudy & Matus-Amat, 2005;Yoon & Otto, 2007) during trace and delay fear conditioning paradigms. The graded involvement may be due to the graded connectivity between the portions of the cortex receiving visual information and the hippocampus, with the dorsal half of the hippocampus receiving more visual information than the ventral pole (Furtak et al., 2007; Kerr et al., 2007) The present results do not make it possible to isolate the roles of dorsal CA1 and ventral CA1 for temporal ordering of visual object information other than to say that dorsal CA1 seems to play a more important role. The data do suggest that dorsal CA1 primarily mediates temporal ordering of visual objects, whereas ventral CA1 only

weakly contributes to temporal ordering of visual objects, a finding supported by the anatomy.

Temporal Processing

In the temporal order for olfactory, spatial locations, and visual objects tasks, lesions of CA1 that produced deficits always reduced the probability that the animal would preferentially explore the earlier of the elements presented. In the present temporal ordering paradigms, control rats reliably choose to preferentially reexplore the odor, location, or object that was presented earlier in the sequence, whereas CA1 lesioned rats show a preference for the latter odor, location, or object presented. This could mean either of two processes could potentially mediate these effects. The rats, it appears, react to a gradient in familiarity in either of two ways: they preferentially explore more the more familiar (e.g., the first element is more familiar because the memory of the first object has had more time to consolidate than the third object), or else they prefer the more novel (or less familiar) alternative (e.g., the first element is more novel because the memory of the first object is weaker then the third object because it occurred earlier in time). Hoge and Kesner (2007) suggest that these impairments may be due to impaired consolidation of the information presented during the study phase. It has been shown previously that lesions to dorsal CA1 do not result in deficits for the identification and exploration of item novelty in rats (Lee, Hunsaker, & Kesner, 2005). In the present task, rats also prefer the novel object when presented with a choice between the first element presented and a novel one. This suggests that, even with lesions to dorsal or ventral CA1, the detection of novelty is unimpaired. This speaks against the hypothesis that control rats explore the first element because it is more novel. The theory postulated by Hoge and Kesner (2007) that the animals prefer the first element because it has been consolidated to a greater extent, fits both the present as well as previous experimental data that demonstrate the role of CA1 in consolidation (Ji, Wang, & Li, 2003; Remondes & Schumann, 2004; Vago, Bevan, & Kesner, 2007).

An alternate explanation that better describes the present data is due to the fact that even though CA1 lesioned animals (either dorsal or ventral) do not show a preference for the first object presented, they do display a preference. Animals with CA1 lesions, as presented in this report as well as in Hoge and Kesner (2007), show a preference for the last object presented in the study phase. This finding suggests that a simple consolidation gradient does not fully explain the present findings. The CA1 lesioned animals express a significant preference for recent items over more remote items, a process that has been attributed to the perirhinal cortex (a recency effect; cf. Brown & Aggleton, 2001). The present data reveal a type of competitive parallel processing involving the perirhinal cortex and CA1 when it relates to expressing a preference to one item over another based on temporal order. Control rats displayed a preference for primacy over recency, suggesting that the hippocampal-dependent processing is favored. After CA1 lesions, the rats displayed a preference for recency over primacy, suggesting that perirhinal-dependent processing is favored, presumably because the hippocampal system became unreliable. It has been shown that lesions to the perirhinal cortex disrupt recency judgments (cf. Brown & Aggleton, 2001) and that lesions to CA1 disrupt a natural preference for items that appeared earlier in a temporal sequence (a primacy effect; cf. Hoge & Kesner, 2007). In the absence of CA1, the rats appear to show a pattern of preferences similar to the pattern attributed to intact perirhinal function.

General Remarks

The present experiments were designed to more thoroughly characterize the role of the CA1 subregion of the ventral hippocampus and dorsal hippocampus for temporal ordering processes. Dorsal CA1 and ventral CA1 were selectively ablated and then the rats were tested in a series of behavioral experiments that stressed temporal processing and ordering of different types of information. The data suggest that the roles of dorsal CA1 and ventral CA1 for temporal processing can be dissociated when the information being processed is unique to either the dorsal or ventral hippocampus. Temporal ordering of spatial locations is subserved by dorsal CA1, which is no surprise because it has been shown that the ventral hippocampus is not as critical as the dorsal hippocampus for spatial information processing (Bannerman et al., 1999, 2002, 2004; Moser & Moser, 1998; but cf. de Hoz et al., 2003; McDonald et al., 2006). Temporal ordering for olfactory stimuli is mediated by ventral CA1, which is supported by reports that the ventral pole of the hippocampus receives a higher amount of olfactory information than the dorsal pole and previous reports of the sparse role of the dorsal hippocampus for olfactory processing (Furtak et al., 2007; Kerr et al., 2007; Steffenach et al., 2005; Witter et al., 2000). In contrast to these examples, it appears that temporal processing of visual information is mediated by both the dorsal and ventral hemispheres of the hippocampus (at least in CA1). Both dorsal CA1 and ventral CA1 lesioned rats showed deficits in the temporal ordering of visual objects, but dorsal CA1 lesioned ratss showed a greater deficit than ventral CA1 lesioned rats. These results suggest that visual information reaches both the dorsal and ventral poles of the hippocampus, and CA1 can temporally process incoming visual information. These data support an alternative hypothesis for ventral hippocampal function, in that it also supports temporal processing similar to the dorsal hippocampus but on different domains of information.

In the present experiment, when there are dorsal-ventral CA1 dissociations, it can be attributed to similar processing of dissimilar domains of information, in other words, the same temporal ordering process is being carried out on different information (for a model of dorsal-ventral homogeneity of hippocampal function, cf. Rudy & Matus-Amat, 2005). This assumption is supported by reports that the dorsal and ventral hippocampus do not efficiently communicate with each other and that they receive different cortical and subcortical projections (cf. Amaral & Witter, 1989; Risold & Swanson, 1996). The present experiment provides evidence that the ventral hippocampus is capable of temporal processing and ordering of information, so long as the information to be temporally processed enters the ventral hippocampus (i.e., odors and visual objects). The present data also suggest that the dorsal hippocampus mediates temporal ordering processes as well, as long as the information to be processed reaches the dorsal hippocampus (i.e., visual and spatial). These results suggest that the ventral hippocampus subserves processes similar to the dorsal hippocampus, along with the anxiolytic functions it subserves.

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