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Concepts in Space: Enhancing Lexical Search With a Spatial Diversity Prime

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Abstract

Informed by theories of embodied cognition, in the present study, we designed a novel priming technique to investigate the impact of spatial diversity and script direction on searching through concepts in both English and Persian (i.e., two languages with opposite script directions). First, participants connected a target dot either to one other dot (linear condition) or to multiple other dots (diverse condition) and either from left to right (rightward condition) or from right to left (leftward condition) on a computer touchscreen using their dominant hand's forefinger. Following the spatial prime, they were asked to generate as many words as possible using two-letter cues (e.g., "lo" → "love," "lobster") in 20 s. We hypothesized that greater spatial diversity, and consistency with script direction, should facilitate conceptual search and result in a higher number of word productions. In both languages, word production performance was superior for the diverse prime relative to the linear prime, suggesting that searching through lexical memory is facilitated by spatial diversity. Although some effects were observed for the directionality of the spatial prime, they were not consistent across experiments and did not correlate with script direction. This pattern of results suggests that a spatial prime that promotes diverse paths

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can improve word retrieval from lexical memory and lends empirical support to the embodied cognition framework, in which spatial relations play a crucial role in the conceptual system.

Keywords: Spatial relations; Conceptual system; Physical and mental search processes; Embodied cognition

1. Introduction

In his 1890 book, *The Principles of Psychology*, William James draws a parallel between searching for a lost concept in our memory and sifting through the rooms of a house for an object: "We search in our memory for a forgotten idea, just as we rummage our house for a lost object" (James, 1890, p. 654). We might intuitively interpret his analogy as suggesting that people might search for desired items in their memory through a mind's eye. Additionally, individuals often exhibit eye movements resembling scanning when faced with the task of swiftly retrieving a concept from memory. Specifically, in challenging situations such as the tip of the tongue phenomenon, people dart their eyes around like there is an actual space in front of them that they need to scan for the desired concept (Ehrlichman & Micic, 2012).

In recent decades, numerous studies have shown the effects of space on cognitive processes, many of them within the embodied cognition framework. Based on the embodied cognition view, space is at the heart of our conceptual system, and we often think in spatial metaphors (Casasanto & Bottini, 2014; Gibbs & Matlock, 2008). For example, people associate positive concepts, pictures, and incidents with the top of a vertical spatial continuum and associate negative ones with the bottom (Brunyé, Gardony, Mahoney, & Taylor, 2012; Crawford, Margolies, Drake, & Murphy, 2006; Meier & Robinson, 2004). In another example, it is found that listening to vignettes containing spatial descriptions, such as "the top of a skyscraper" or "the bottom of a canyon," results in appropriate upward and downward eye movements, suggesting that spatial characteristics of linguistic input affect online visuospatial processing (Spivey & Geng, 2001; Spivey, Tyler, Richardson, & Young, 2000). These findings highlight the importance of spatial cognition in shaping our cognitive experiences and reveal the intricate relationship between space and cognition.

Other studies have provided evidence for spatial behavior of the eyes and hands on numerical cognition (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). In a more recent study, for example, it is shown that, in solving different arrangements of water jar problems with either addition or subtraction operations, priming participants with left-arm motion causes them to not only pay more attention to the left side of the presented tasks but also to use significantly more subtractions relative to the right-arm priming motion (Werner, Raab, & Fischer, 2019). These results are in line with the embodied cognition framework in which, for left-to-right writing systems such as English, left is associated with subtractions and right is associated with additions (Knops et al., 2009; Pinhas, Shaki, & Fischer, 2014).

This connection between spatial relationships of the body and cognitive processes of the mind has led to a wide variety of social/behavioral priming studies suggesting that implicitly activating certain conceptual representations can sometimes influence social or motor behavior (Bargh, 2022; Williams, Huang, & Bargh, 2009). A meta-analysis of 133 such studies reported a reliable (though small) result of priming that was robust across methodologies (Weingarten et al., 2016). However, it warrants acknowledging that some of those priming studies have failed to replicate in specific experiments. Some of the failures may be due to theoretical and methodological weaknesses (Locke, 2015), but many of them appear to be due to miscommunication about the terms being used and the claims being made by various researchers (Sherman & Rivers, 2021a, 2021b). Therefore, the present study makes great efforts to maximize experimental controls, replicate the result across two experiments, conduct an omnibus analysis of the combined data, and motivate the predictions with a clear mechanistic theoretical account.

This mechanistic theorical account is inspired by two decades of embodied cognition research suggesting that cognitive and linguistic mechanisms use some of the same formats of representation and processing that sensorimotor mechanisms use (Barsalou, 1999, 2023). One of those common formats is spatial topography. For example, if similar concepts are encoded by similar representational resources in a human mind, then it makes sense that two related concepts would be represented nearby one another in the state space of that mind. A spatial topography naturally emerges from that simple proximity constraint. Clusters will form of similar/related concepts and long distances will manifest in between dissimilar concepts. This spatial clustering phenomenon is evident in various studies.

For instance, when Louwerse and Zwaan (2009) applied latent semantic analysis (Landauer & Dumais, 1997) to thousands of *Wall Street Journal* articles that mentioned any of the 50 most populated cities in the United States, and applied multi-dimensional scaling (MDS) to the data, they found that cities that are physically nearby one another tended to form tight clusters in the MDS plot, and cities that are physically far from one another tended to also be far from one another in the MDS plot. If the statistics of our exposure to concepts (such as city names) naturally encourages appropriate spatial clustering in their co-occurrence state space, then it should not be surprising that our minds might encode them with properties of spatial clustering as well. Similarly, when Rhodes and Turvey (2007) asked participants to name as many animals as they could think of, the inter-response intervals (i.e., durations between name productions) revealed that participants were quickly naming several animals from a cluster in mental state space and then pausing while they eventually found another cluster in mental state space from which they could again quickly name several animals. The resulting Lévy-flight statistics of this time series (where clusters of short intervals are occasionally punctuated by a long interval) are remarkably similar to the Lévy-flight statistics of animals actually foraging in the wild, where they make many short movements within a spatial cluster and then occasionally make a long movement to a new cluster (Kello et al., 2010). Moreover, when Montez, Thompson, and Kello (2015) asked participants to make similarity-based clusters of animal names (printed on magnets) on a large whiteboard, they did so in a manner that corresponded well with various taxonomic categories and even correlated well with the inter-response intervals of a different set of participants who generated those animal names from recall.

Taken together, these studies indicate how our knowledge about external spatial relations is projected onto abstract cognitive processes. For instance, upon finding that a visual diagram depicting arrows converging onto a central point primed participants to be better at solving Karl Duncker's famous radiation problem, Gick and Holyoak (1983) suggested that the spatial prime induced an abstract conceptual schema of *convergence* that assisted participants in arriving at the solution. In multiple replications, that work was extended by including animated primes (Pedone, Hummel, & Holyoak, 2001) and even inducing participants to make convergence-based eye-movement patterns on the problem's diagram itself (Grant & Spivey, 2003; Thomas & Lleras, 2007, 2009). Relatedly, Guerra and Knoeferle (2014, 2017) showed participants short videos of two objects moving close together or of two objects moving apart from one another and then had them read sentences noting the similarity between a pair of abstract concepts (e.g., battle and war) or noting their dissimilarity (e.g., peace and war). After being primed by a video of two objects moving closer together, participants had briefer eye-gaze times on words in the sentences about similar concepts, compared to their eye-gaze times on words in the sentences about dissimilar concepts—and vice versa for when primed with the two objects moving apart. The video of concrete objects moving together or apart had primed a concept of closeness or farness that facilitated reading of the sentences describing a corresponding similar/dissimilar relation between abstract concepts.

Todd and Hills (2020) take this role of spatial relations in much of human cognition a little further and argue that "foraging in mind" relies on the same cognitive mechanisms used to forage in physical space. They argue for a common underlying process by showing that internal search strategies for finding words in sets of letters (such as the game Scrabble) can be *spatially primed* by different environments. Specifically, in two studies (see Hills, Todd, & Goldstone, 2008, 2010), they report that participants who had searched a virtual environment to find clumpy distributed tokens spent more time finding words that can be made of each letter set in the Scrabble task, relative to participants who had searched the virtual environment with diffusely distributed tokens. These results suggest how searching through a seemingly dissimilar, abstract task relies on the same basic mechanisms used to search physical space. According to Hills et al., and echoing William James, foraging in mind uses the same ancient mental procedures as foraging for food in one's physical environment.

This search through mental space can be conceptualized as a trajectory through an attractor landscape (Spivey, 2007). In this landscape, each attractor basin functions as a concept (such as an animal name or some other word) that may have a strong attractive force (i.e., a deep well in the surface) or a weak attractive force (i.e., a shallow well in the surface) due to high or low prominence or accessibility. At any point in time, the degree of prominence or accessibility for a given concept could be the result of a combination of situational constraints, lexical frequency, and contextual diversity (Adelman, Brown, & Quesada, 2006). The manner in which these attractor basins are arranged on the landscape will correspond to their similarity or relatedness, manifested as their spatial clustering. Highly accessible concepts that are well-traveled make for large and deep attractor basins in semantic state space. These large attractor basins often develop common pathways that naturally lead from one to the next in a relatively linear repeated sequential fashion. For example, in English, we often hear "salt and pepper" but rarely hear "pepper and salt." By contrast, less-accessible ideas, which are rarely visited in the state space, make for small shallow attractor basins. They are less likely to have

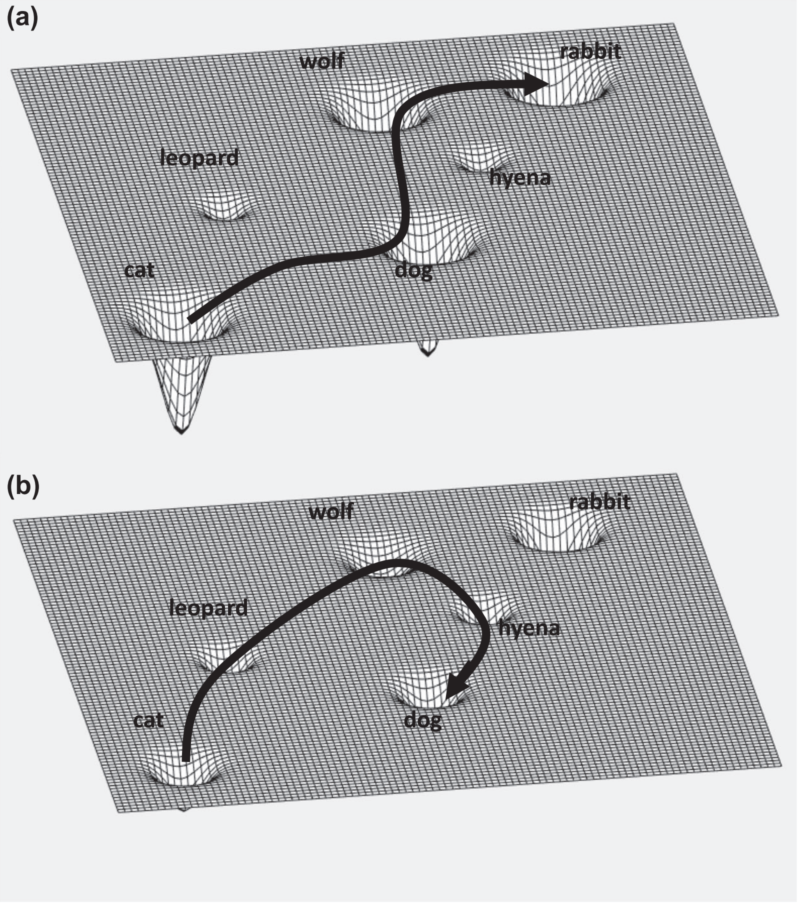

Fig. 1. Panel (a) illustrates a schematic example of an attractor landscape with four strong attractor basins and two weak ones. In that case, the trajectory visits only those four strong attractors. Panel (b) shows a “flattened” version of the same landscape, thus allowing the trajectory to visit the weak attractor basins as well; producing five lexical items in total.

well-traveled pathways that link them. Therefore, transitions from one to another in the flatter regions of this landscape are less linear and predictable, more spontaneous and unexpected.

For example, Fig. 1a displays a schematic example of a set of attractor basins, some deep and some shallow, that would all compete to pull the state of the system (i.e., the state of mind) toward themselves. The trajectory plots a path where the system might visit just the four deepest wells (strong attractor basins, which become repellers once visited), and thereby name only those four highly accessible words. However, if a cognitive construct of “spatial diversity of paths” had been primed (perhaps by simply having the person trace out multiple expanding paths with their finger), we hypothesize that the attractor landscape may change subtly to allow for a more diverse, nonlinear, and creative trajectory with multiple prominent and less-prominent visitation points.

When the cognitive attractor landscape is perturbed by external influences, it can change in subtle but important ways. For example, Beda and Smith (2022) outline a variety of cognitive practices to overcome the fixations that past experience imposes on the creative process. In addition to cognitive practices that help a person get unfixated from those prominent but sub-optimal choices in the search space, other perturbations could include hormones (Taylor et al., 2022), psychedelics (Roseman, Leech, Feilding, Nutt, & Carhart-Harris, 2014), transcranial direct current stimulation (Chrysikou et al., 2013), or even something as simple as a *spatial diversity prime*, to slightly "flatten the attractor landscape." Fig. 1b illustrates a schematic example of a flattened version of the same landscape. When the landscape is slightly flattened, the difference in strength among the various attractors is reduced, thus allowing less-accessible uncommon concepts to be visited in the sequence and allowing a more nonlinear trajectory to form that visits more basins and generates more novel ideas.

Informed by these accounts of the spatial embodiment of cognition, we employed a novel priming technique to investigate the effects of spatial relations on searching through concepts in two languages with opposite script orientations: Persian and English. The priming technique employed spatial patterns designed to unobtrusively prime spatial diversity (diverse or linear) and directionality (leftward or rightward). Participants duplicated spatial patterns on a computer touchscreen using their dominant hand's forefinger and then engaged in generating words for two-letter stems. We predicted that diverse spatial priming, especially when it is in line with script direction, would lead to greater conceptual diversity and, therefore, a higher number of word retrievals for the given letter sets. This prediction stems from the notion that a physically diverse environment might stretch and flatten the memory space, thereby leading to longer search trajectories and facilitating a larger pool of concept retrievals. In other words, conceptual search might be diversified when a cognitive construct of spatial diversity of paths is primed.

2. Experiment 1

In the first experiment, Persian participants were primed by spatial patterns designed with different arrangements of dots presented on a computer touchscreen and then were asked to generate words for Persian two-letter sets. Specifically, participants connected either a single target dot to another dot (linear condition) or multiple dots (diverse condition) and either moved their hands from left to right (rightward condition) or from right to left (leftward condition, see Fig. 2). Based on the aforementioned findings, we hypothesized that spatial diversity and consistency with Persian right-to-left script orientation would lead to conceptual diversity and, therefore, significantly greater word generations.

2.1. Method

2.1.1. Participants

Forty-eight undergraduates (38 female, $M_{\text{age}} = 20.92$ years, $SD = 2.03$) from the psychology department at the University of Tehran participated in this Institutional Review Board (IRB)-approved experiment in exchange for course credit. All participants were Persian native

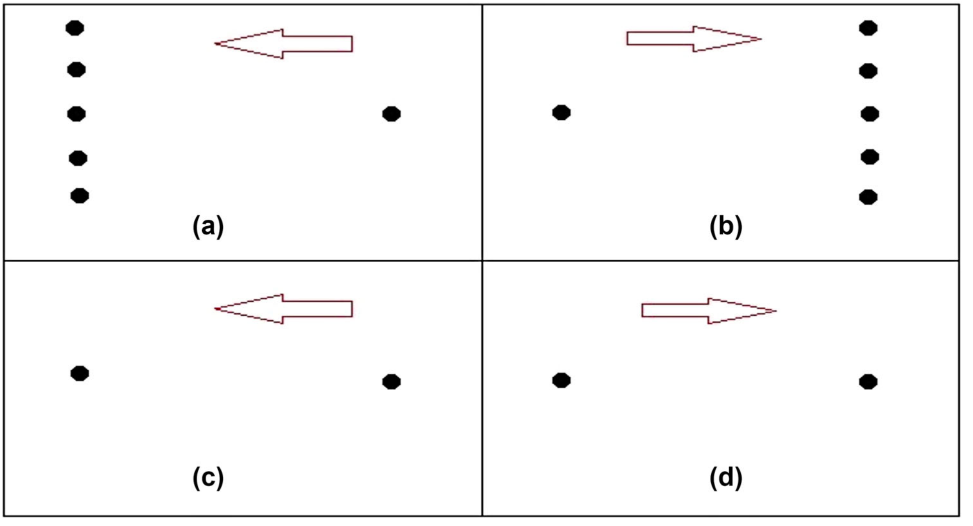

Fig. 2. Illustration of spatial priming tasks. Prior to presenting a two-letter set, participants were instructed to attach one of the dots shown as their priming stimuli. It should be noted that the arrows depicted in the figure were not displayed during the experiments; instead, a pattern demonstrating how the dots should be connected was presented at the beginning.

speakers and were right-handed. In a between-subjects factorial design, participants were randomly assigned to one of the four experimental groups. They were unfamiliar with the presented tasks and were tested individually in a laboratory setting.

2.1.2. *Spatial priming tasks*

We assessed spatial diversity and script direction using a novel task, depicted in Fig. 2. This task consisted of four different types of dot arrangements that participants needed to connect on a touchscreen monitor using their dominant hand's forefinger: (a) connecting a target dot on the right side to multiple dots on the left side of the touchscreen, (b) connecting a target dot on the left side to multiple dots on the right side, (c) connecting a target dot on the right side to a single dot on the left side; and finally, (d) connecting a target dot on the left side of the touchscreen to a single dot on the right side. By employing a between-subjects factorial design, we aimed to prime diversity and left and rightward directionality for both Persian and English languages, which possess opposite script directions. The tasks were programmed using Python 3.8 and presented on a 21.5" touchscreen monitor at a distance of approximately 50 cm away from the participants' eyes.

2.1.3. *Persian lexical search task*

We created 12 two-letter sets for the search task. We ensured each letter set had at least five Persian words associated with them using the Dehkhoda Persian dictionary (Dehkhoda, 1998). For example, an English equivalent for the letter sets would be "LO…," which could lead to word generations such as "love," "locomotive," "lobster," "lotion," and "lost."

Regardless of the spatial priming tasks they were assigned to, all participants searched for words using the same 12 pairs of letters, one per trial.

2.1.4. Procedures

Upon signing a consent form and filling out a demographics form, participants were randomly assigned to one of the four spatial priming tasks and seated in front of a touchscreen monitor to start the experiment by reading the instructions in Persian. A video showing how the dots needed to be connected was then displayed to further clarify the task for the participants. The video consisted of black lines that, depending on the participants' spatial priming group, would start from the target dot and, with a constant speed, would attach to the dot(s) on the other side.

Subsequent to the spatial priming task, participants were presented with a two-letter set in the middle of the monitor and had 20 s to generate, with pen and paper, as many words as they could that began with those two letters. Once they finished their word generation for a trial, the next trial would begin by repeating the spatial priming task, followed by another word generation task, until all 12 trials were completed.

Participants were instructed that proper nouns, such as names of places or people (e.g., *Lo*ndon, *Lo*ra), were disallowed. They were also instructed to avoid adding different suffixes to the same stem word (e.g., love, lover, lovely, and loved), as these variations would be counted as a single word. It was emphasized that there would be no penalties for incorrect words. Therefore, if participants were unsure about the acceptability or the spelling of a word, they were advised to still write it down and continue searching for more words.

A beep was played when their 20 s for word production was up. When they heard the beep, they had to put down their pen. There was no time limitation for attaching the dots in the prime, and their 20 s word generation time started only after pushing the "Enter" button on the spatial priming trial.

2.2. Results and discussion

There were 12 participants in each of the four spatial priming groups. We first excluded proper nouns and words that were illegible, incomplete, or repeated. Then, the average number of remaining produced words for each participant was calculated for the subsequent statistical analysis.

A factorial ANOVA was applied to compare the effects of the four spatial priming conditions. First, as predicted, results showed a significant main effect of diversity, $F(1,44) = 17.71$, $p < .001$, $\eta_p^2 = .23$. The main effect of directionality, although marginally significant, at the conventional alpha level of .05 did not attain significance, $F(1,44) = 3.33$, $p = .07$, $\eta_p^2 = .04$. Second, the results revealed that there was a statistically significant interaction between diversity and directionality on the number of generated words, $F(1,44) = 10.90$, $p = .002$, $\eta_p^2 = .14$.

To further explore the main effect of diversity, an independent samples *t* test was performed. The analysis revealed that participants in the diverse conditions ($M = 3.44$, $SD = 0.64$) generated significantly more words compared to participants in the linear conditions ($M = 2.85$,

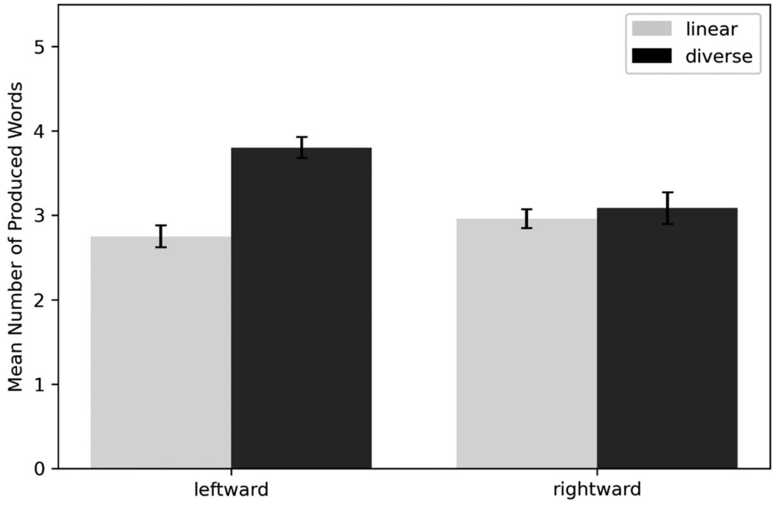

Fig. 3. Mean number of produced words in the lexical search task across the four spatial priming conditions in Experiment 1 (Persian participants). Error bars show the standard error of the mean.

Table 1
Comparisons of the various models to the null model in Experiment 1

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error %
Null model	0.200	0.001	0.005	1.000	
Directionality + diversity + directionality × diversity	0.200	0.878	28.802	734.784	1.777
Diversity	0.200	0.065	0.277	54.108	1.4×10^{-7}
Directionality + diversity	0.200	0.055	0.234	46.268	0.708
Directionality	0.200	8.009×10^{-4}	0.003	0.670	0.007

SD = 0.41), $t(46) = 3.73$, $p < .001$, two-tailed, $d = 1.08$. Further examination of the interaction effect using Tukey's test revealed that the leftward diverse condition ($M = 3.80$, $SD = 0.41$) resulted in significantly more words, compared to all other conditions (Fig. 3); the leftward linear condition ($M = 2.75$, $SD = 0.42$), the rightward diverse condition (M = 3.08, SD = 0.62), and the rightward linear condition ($M = 2.96$, $SD = 0.37$; all *p*s < .01).

In addition to the factorial ANOVA, we conducted a Bayes Factor (BF) analysis, following guidelines outlined by van Doorn et al. (2021), to compare different models. We analyzed the data with JASP (JASP Team, 2019), employing its default noninformative prior. For detailed information, including distribution plots, data, and input options, an annotated .jasp file is available at https://osf.io/37ftj/.

Table 1 presents the model comparison results. The model including directionality, diversity, and the interaction between directionality and diversity received the highest posterior probability (P(M|data) = 0.878) and the Bayes factor (BF10 = 734.784) provided strong evidence in favor of this model over the null model. The error percentage for this model was

1.777%. The model including only diversity had a posterior probability of .065 (P(M|data) = 0.065) and a Bayes factor (BF10) of 54.108, indicating strong evidence in favor of this model over the null model. The error percentage for this model was < 0.001%, demonstrating great stability of the numerical algorithm used to obtain the results. The directionality model, focusing solely on script direction, had a Bayes factor (BF10) of 0.670 indicating weak evidence in favor of the directionality model. The error percentage for this model was 0.007%.

Overall, these findings support our hypotheses that greater spatial diversity (one-to-multiple conditions) and consistency with Persian script directionality (right-to-left conditions) induce greater conceptual diversity, resulting in more word productions. This pattern of results suggests that searching through lexical memory is facilitated with greater spatial diversity, especially when diversity is in line with the Persian leftward script direction. In other words, people might rely on spatial relations to explore words within memory space, which lends empirical support to the embodied cognition framework according to which spatial relations play a crucial role in the conceptual system.

3. Experiment 2

We aimed to replicate the first experiment's findings in English in the second experiment. Given that English is a left-to-right language, our hypothesis for directionality flipped. Specifically, we predicted that rightward script directionality (i.e., connecting the dots from left to right) would result in better performance in finding words for English two-letter sets. With regards to diversity, we again expected that greater spatial diversity (i.e., connecting one dot to multiple other dots) should reliably improve word generation performance.

3.1. Method

3.1.1. Participants

In the English version of the experiment, 63 undergraduates (42 female, $M_{\text{age}} = 19.37$, $SD = 1.27$) from the Psychology Department at Mississippi State University participated in the IRB-approved study in exchange for course credit. All participants were native English speakers. As in the first experiment, they were randomly assigned to one of the four spatial priming tasks in a between-subjects factorial design and tested individually.

3.1.2. Spatial priming tasks

The exact spatial priming tasks used in the first experiment were utilized in the English version (Fig. 2). That is, there were the four arrangements of dots that comprised a single target dot that needed to be connected to either one other dot (linear condition) or multiple other dots (diverse condition) and either from left to right (rightward condition) or from right to left (leftward condition) on a computer touchscreen by participants' dominant hand forefinger. The tasks were presented on a 21.5'' monitor touchscreen at a distance of about 50 cm from the participants.

3.1.3. English lexical search task

Instead of pairs of Persian letters, in the second experiment, letters of the English alphabet were placed next to each other to make up the pairs of letters for the English lexical search task. A set of 10 pairs of letters with at least five words beginning with them in the Oxford English Dictionary (Simpson & Weiner, 1989) was chosen for the search task.

3.1.4. Procedure

The procedure for Experiment 2 closely followed that of Experiment 1, with the exception of using English letter sets instead of Persian. The response exclusion criteria remained unchanged. Participants underwent the same tasks and instructions as in the previous experiment, but this time, the letter sets were composed of English letters.

3.2. Results and discussion

Four participants were left-handed and excluded from the analysis. This left us with 59 participants (14–16 per condition). As in Experiment 1, the average number of produced words for each participant was recorded for the statistical analysis.

We first conducted a factorial ANOVA to test the main effects of the diversity and directionality, as well as their interaction. Unlike in Experiment 1, the interaction between diversity and directionality was not significant, $F(1,55) = 0.10$, $p = .76$. Therefore, we left the interaction effect out of the model and performed the factorial ANOVA only with the main effects of diversity and directionality. Consistent with Experiment 1, the results showed a significant main effect of diversity, $F(1,56) = 4.61$, $p = .036$, $\eta_p^2 = .06$. In addition, in this experiment, the main effect of directionality was also significant, $F(1,56) = 11.39$, $p = .001$, $\eta_p^2 = .16$.

The results of independent samples *t* tests replicated the diversity effect in Experiment 1, meaning that participants in the diverse conditions ($M = 4.28$, $SD = 0.75$) had a significantly better lexical retrieval performance relative to those in the linear conditions ($M = 3.87$, $SD = 0.76$), $t(57) = 2.025$, $p = .047$, two-tailed, $d = .53$. Moreover, we observed that leftward conditions ($M = 4.40$, $SD = 0.70$) led to significantly better word retrieval than rightward conditions ($M = 3.77$, $SD = 0.73$), $t(57) = 3.307$, $p = .002$, two-tailed, $d = .86$, in contrast to the English rightward script orientation (Fig. 4).

Alongside the factorial ANOVA, and similar to the previous experiment, we performed a Bayes factor analysis in order to confirm the results of our frequentist statistical models. The data were examined using JASP (JASP Team, 2019), utilizing its default noninformative prior. For comprehensive details, including distribution plots, data, and input options, an annotated .jasp file can be accessed at https://osf.io/37ftj/.

The model comparison results are presented in Table 2. The model including both diversity and directionality received the highest posterior probability of 0.514 (P(M|data) = 0.514) and had a Bayes factor (BF10) of 46.657, providing strong evidence in favor of this model over the null model. The error percentage for this model was 0.652%. On the other hand, the model including only diversity obtained a posterior probability of 0.017 (P(M|data) = 0.017) and a Bayes factor (BF10) of 1.583, indicating weak evidence in favor of this model over the null model. The error percentage for this model was 0.009%. Last, the directionality model,

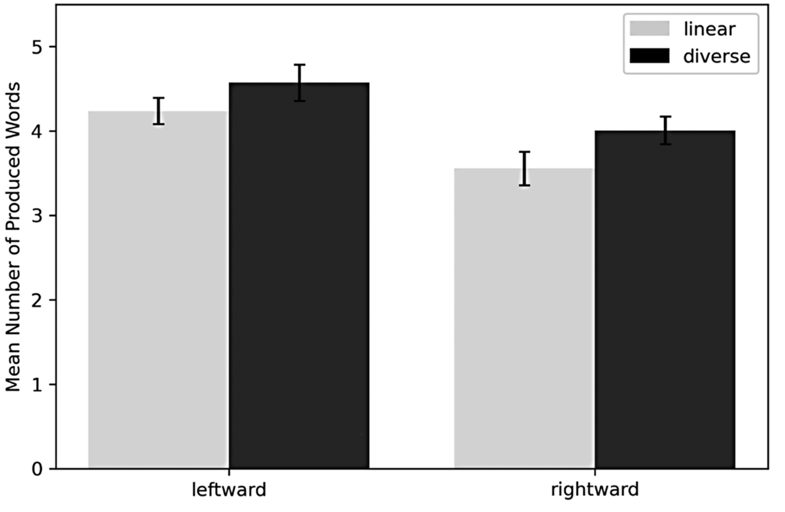

Fig. 4. Mean number of produced words in the lexical search task across the four spatial priming conditions in Experiment 2 (American participants). Error bars show the standard error of the mean.

Table 2
Comparisons of the various models to the null model in Experiment 2

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error %
Null model	0.200	0.011	0.045	1.000	
Diversity + directionality	0.200	0.514	4.227	46.657	0.652
Directionality	0.200	0.258	1.389	23.407	2.548×10^{-7}
Diversity + directionality + diversity ✻ directionality	0.200	0.200	1.000	18.162	0.969
Diversity	0.200	0.017	0.071	1.583	0.009

focusing solely on script direction, obtained a posterior probability of 0.258 (P(M|data) = 0.258) and a Bayes factor (BF10) of 23.407, indicating strong evidence in favor of the directionality model over the null model. The error percentage for this model was < 0.001%.

Overall, these findings, while replicating the diverse effect of the first experiment, do not support the script directionality effect because the effect of directionality did not flip from leftward to rightward when going from Persian to English. Although these findings cast substantial doubt on the script directionality effect in the search process through the conceptual system, they bolster the evidence that searching through the conceptual system is facilitated by a spatially diverse visuomotor priming stimulus, as this is the result that clearly replicates across the two experiments. The results from these two experiments highlight people's reliance on spatial relations in exploring words in lexical memory.

Table 3
Bayesian regression analysis results for the combined data

Parameter	Estimate	Est. Error	95% CI Lower	95% CI Upper	Rhat	Bulk ESS	Tail ESS
Intercept	3.50	0.15	3.21	3.80	1.00	21232	24,316
Diversity (diverse)	0.75	0.21	0.35	1.16	1.00	19,015	22,493
Directionality (rightward)	−0.17	0.20	−0.57	0.23	1.00	18,561	22,431
Diverse × rightward	−0.52	0.28	−1.08	0.03	1.00	16,779	20,462
Sigma	0.79	0.06	0.69	0.90	1.00	32,012	22,762

4. Combined data results

To maximize statistical power, and to directly assess the strength of empirical evidence in favor of the research hypotheses, we combined the data from both experiments (Persian and American participants) into one dataset and conducted a Bayesian regression analysis. The model was estimated using the brm function in R with a Gaussian family distribution and included the main effects of diversity and directionality, as well as their interaction, and consisted of all 107 (Persian and American) participants.

The results are summarized in Table 3 (ESS=Effective Sample Size). As with each experiment on its own, the main effect of diversity in this combined analysis was again found to be statistically significant, with a positive estimate of 0.75 and a 95% Credible Interval (CI) (0.35, 1.16) that does not span across zero. This suggests that, throughout both Persian and English experiments, the diversity prime is associated with a higher production of words. On the other hand, the main effect of directionality was not statistically significant in this combined analysis, as the estimate is −0.17 and its 95% CI (−0.57, 0.23) does span across zero. This indicates that there is no clear evidence of a direct effect of directionality on average word production.

Notably, the interaction between diversity and directionality was also found to be statistically nonsignificant, with an estimate of −0.52 and a credible interval (95% CI [−1.08, 0.03]) that spans across zero. This indicates that, pooled across both experiments, the relationship between diversity and average word production did not reliably differ depending on the direction of the spatial primes. The family-specific parameter, sigma, representing the residual standard deviation, was estimated to be 0.79 (95% CI [0.69, 0.90]), indicating the amount of unexplained variability in the average word production.

5. General discussion

In the present paper, we investigated the effects of spatial relations on searching through the conceptual system in two languages with opposite script directions. In both Persian and English, greater spatial diversity in the priming stimulus facilitated the search process for word retrieval from lexical memory. This main effect of spatial prime diversity was present in

Experiment 1 (Persian), present in Experiment 2 (English), and also present in the combined analysis of both experiments. In the Persian experiment, the main effect of directionality was not statistically significant. However, there was a significant interaction between diversity and directionality, such that spatial diversity had a greater impact when the dots were connected from right to left, consistent with Persian leftward script orientation. In the English experiment, no such interaction was observed, although the directionality manipulation had a significant main effect that was inconsistent with English rightward script orientation. In the omnibus analysis that combines Experiments 1 and 2 (see Table 3), we did not find statistically significant evidence for a main effect of directionality or an interaction between directionality and diversity. Therefore, it may be premature to offer interpretations for the occasional effect of spatial prime directionality in these experiments. What we *can* conclude from the results concerning directionality in our experiments is that we do *not* see any evidence for a difference between Persian right-to-left readers and English left-to-right readers in these spatial prime directionality manipulations. As the results for the diversity prime are consistent across all our tests, and the results for directionality are inconsistent across them, we will focus the rest of our discussion on the results of the spatial diversity manipulation.

Overall, this pattern of results with the spatial diversity prime suggests that the conceptual search processes for finding words, at least within lexical memory, may be influenced by physical spatial relations. This conclusion extends Hills and colleagues' work on foraging in mind, who argue that spatial foraging strategies carry over to mental foraging and use similar underlying mechanisms (Hills et al., 2008, 2010). It also fits with the research showing that the brain has a common biological basis for spatial and abstract goal-directed cognitive processes (Hills, 2006). We propose that priming the concept of diversity via spatial relations is transferred to the mental search process and facilitates access to diverse and distant concepts in the brain during the lexical search task.

If the increased ability to search lexical state space is due to a process like a "flattening of the attractor landscape," as suggested in Fig. 1, a question still remains as to the exact mechanism by which the spatial prime induces this flattening. In a somewhat-related treatment of lexical processing, Mirman and Magnuson (2008) explored the temporal dynamics of an attractor network simulation of written word recognition. They found that lexical items that have many neighbor words (with many of the same letters) that are nearby in state space tend to exhibit *slower* processing times because the nearby neighbor words attract the state of the system toward them, thus delaying its ability to settle into the correct lexical item's attractor basin. By contrast, the very same attractor network demonstrated that alternative lexical items that have the same number of neighbor words but far away in state space will often exhibit *faster* processing than baseline. Thus, it is not simply the number of neighbor words that influences processing time but where they are in state space relative to the target lexical item. Inspired in part by that mechanistic account of lexical attraction effects, we speculate that, by placing a visuospatial emphasis on *multiple directions and multiple destinations*, the diverse prime in our experiments may be reducing the attraction effects of the few prominent nearby lexical items in the attractor landscape and increasing the relative attraction effects of the many less-prominent lexical items. The resulting flattening of that landscape could allow the search process to avoid falling into only the prominent lexical items that are nearby the system's current state at any point in time and instead explore less-prominent lexical items whose attractor basins are now closer to equivalent in strength as the others. To mathematically achieve this flattening of the landscape in an attractor network, all that may be needed is a simple exponential reduction in the strengths of all attractors (or all network connection weights), where the exponent is between 0 and 1.

Further exploration of the effects of this spatial prime will need to be pursued to tease out details of this mechanistic account. For example, does the diverse spatial prime induce a wider search of the state space than the linear spatial prime because it involves a wider spread through two-dimensional space, or simply because it involves five events and the linear prime involves only one event? To test this alternative account, future work will compare the prime with five diverse paths to one with a repeated set of five nondiverse paths. These replications and extensions will also conduct the follow-up experiments to include a more diverse population of participants and to ensure that all experimental conditions are completely double-blind. Future work will also compare the diversity prime's effects on this divergent-thinking task to its effects on a convergent-thinking task.

In general, the effects of spatial relations on searching through concepts have notable consequences for traditional theories about the conceptual system. For a long time, theories in cognitive science were dominated by the assumption that an encapsulated system of amodal logical computation can only handle symbolic concepts and that their representations are independent of body and space (e.g., Fodor, 1983; Mahon & Caramazza, 2008). These traditional amodal approaches cannot easily predict the interaction between concepts and spatial sensorimotor activities. In contrast, our results support the embodied cognition framework in which spatial sensorimotor experience plays a crucial role in the conceptual system (e.g., Barsalou, 1999; Lakoff & Johnson, 1980). Our conceptual system may be built, at least in part, out of representations of our physical experiences in space and action.

Without people's intention or awareness, spatial diversity priming stimuli are shown to influence their lexical search processing and their performance in finding words based on letter sets. This suggests that spatial diversity can impact people's search process through lexical state space. Future investigations are needed to further specify the mechanisms by which spatial relations affect people's performance in finding words. Moreover, we imagine that similar spatial priming techniques will be effective in other domains such as problem-solving (both divergent and convergent), goal-pursuing, and decision making. Overall, our findings highlight the ease with which aspects of spatial relations can improve performance in searching lexical memory for finding concepts through priming and activating diversity during the search process.

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