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A Data-Driven Study on Spatial Network of Learning Facilities in Urban Areas

Focusing on Centrality and Educational Disparity

도시 학습 시설의 공간적 네트워크에 대한 데이터 기반 연구

중심성과 교육 격차를 중심으로

주 저 자 : 이기쁨 (Lee, Gi-bbeum) 한국과학기술원 문화기술대학원 박사과정

교 신 저 자 : 이지현 (Lee, Ji-Hyun) 한국과학기술원 문화기술대학원 교수
jihyunlee@kaist.ac.kr

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Abstract

The spatial connectivity of learning facilities (LFs) affects educational accessibility and learner behavior, serving as a key factor in designing urban educational environments. This study proposes a method for analyzing the distribution of local LFs using spatial big data and network analysis. The network of 788 LFs, including elementary, middle, and high schools, academies, tutoring centers, and libraries, across 5 boroughs in Daejeon was analyzed. Centrality measures were applied to assess the proximity of LFs and identify hubs within the network. Results showed the centrality distribution reflects the east-west educational disparity in Daejeon. Additional observation with 99 participants in a virtual environment (VE) replicating a library revealed learners' behavior tendencies. Results showed that network analysis can be applied to assess LFs' connectivity and VEs can be used to redesign learning environments, providing a practical tool for local governments and city planners to design bands of learning facilities.

Keyword

Learning facility(학습 시설), Centrality(중심성), Data-driven urban analysis(데이터 기반 도시 분석)

요약

학습 시설들의 공간적 연결성은 교육 접근성과 학습 행태에 영향을 미치기 때문에 도시의 교육 환경 설계에서 중요하게 여겨진다. 본 연구는 공간 빅데이터와 네트워크 분석을 기반으로 지역 학습 시설의 분포를 분석하는 방법을 제안한다. 대전시의 5개 자치구 안에서 초·중·고등학교, 학원, 교습소, 도서관을 포함한 788개 학습 시설의 네트워크를 구축하였고, 중심성 계산으로 네트워크의 허브 시설을 도출하였다. 그 결과, 네트워크의 중심성 분포가 대전시 교육 환경의 동서 격차를 반영하는 것으로 나타났다. 또한, 디지털 환경을 이용하여 학습 시설의 고립을 완화할 방법을 탐색한다. 가상 환경에 재현된 도서관에서 참가자 99명의 행동 데이터를 분석하여 행동 경향을 도출하였다. 본 연구는 학습 시설의 접근성 평가 및 학습 환경 재구성을 위해 네트워크 분석을 활용할 수 있음을 보여준다. 향후 지방자치단체 및 도시 설계자가 학습 시설 그룹을 설계하기 위해 해당 방법을 활용할 수 있다.

Content

1. Introduction

The design and spatial distribution of learning facilities (LFs) impact educational accessibility and engagement of a local environment. Effective educational environments are not confined to a single facility; instead, they emerge from a network of interconnected facilities that support diverse learning routines. In South Korea, for example, students frequently move between schools, local libraries, and private academies for after-school learning. To accommodate such movement patterns, public and private LFs should be planned within walkable distances. It is crucial to analyze the spatial connectivity of LFs through walkability assessments. Moreover, a recent study[1] shows that digital/virtual visit experience can encourage inclination toward isolated places. Thus, we suggest that virtual spaces of isolated LFs will contribute to connecting local learning communities. This perspective highlights the potential of integrating physical and virtual spaces as a means of redefining the role of libraries within the urban learning infrastructure.

In this study, we propose an integrated approach combining spatial network analysis and virtual environments (VEs) to inform the design of more accessible and engaging LFs. First, we analyzed the network of LFs in Daejeon City, evaluating their spatial distribution through walkability and proximity metrics. Using a large dataset of mobile phone data, we measured the distances and centralities between LFs with a specific focus on adolescent movement patterns. Next, a representative LF with limited centrality was replicated in a 3-dimensional VE, Mincraft. Finally, we investigated participants' virtual visit experience within the VE. Participants' spatial behavior within the VE and changes in their intent to visit the physical facility were analyzed.

By integrating these two approaches, this study bridges the analysis of local educational connectivity with an exploration of learner behavior in LFs. The network analysis identifies structural disparities in educational connectivity, while the VE analysis investigates whether digital engagement can help mitigate these disparities by influencing learner behaviors. By tracing and examining learners' movements within the VE, we assess how virtual experiences can enhance awareness and recognition of physical LFs. This approach provides insights into the role of digital interventions in urban educational infrastructure.

1) Chang, M. et al., 'The influence of virtual tour on urban visitor using a network approach,' 2023b, Advanced Engineering Informatics, 56, p.102025.

2. Literature Review

2-1. Distributions of Learning Facilities

The spatial distribution and connectivity of LFs shape local educational accessibility, leading to disparities in resource availability[2]. Connectivity among LFs enhances learning opportunities and reduces regional educational disparities. For instance, spatial connectivity is essential for strengthening cooperation among LFs and fostering balanced local development[3]. Greater proximity between LFs increases collaboration opportunities among learners[4], ultimately improving learning performance[5]. Nevertheless, LFs are often unevenly distributed, reflecting socioeconomic patterns. Such overcrowded schools and limited educational infrastructure

2) Gilblom, E. A., & Sang, H. I., 'Schools as market-based clusters: Geospatial and statistical analysis of charter schools in Ohio,' 2019, Education Policy Analysis Archives, 27, p.15.

3) 박천보, 최준성, '대도시 교육연구시설의 입지선정 및 평가에 관한 연구', 2017, 한국산학기술학회논문지, 18(11), p.677.

4) Miranda, S., & Claudel, M., 'Spatial proximity matters: A study on collaboration,' 2021, Plos one, 16(12), p.0259965.

5) van der Wouden, F., & Youn, H., 'The impact of geographical distance on learning through collaboration,' 2023, Research Policy, 52(2), p. 104698.

exacerbate long-term learning inequalities[6].

As for planning the facilities, recent studies have emphasized integrating essential local amenities—such as education, healthcare, and commercial spaces—within a 15-minute walking radius[7]. Similarly, LFs should be positioned within walkable distances to ensure accessibility for learners[8]. While high-density urban areas often provide such accessibility, suburban and peripheral regions face significant gaps in public service availability, including LFs[9]. This disparity underscores the need for data-driven analyses of LF connectivity to better understand and optimize local learning environments.

2-2. Connectivity via Virtual Spaces

As discussed in the previous section, certain facilities are unevenly distributed within local environments. Libraries, as a major category of LFs, often exhibit low proximity to both other LFs and residential areas[10], despite their expected role as information hubs and important public spaces [11][12][13]. While prior initiatives have improved access to library resources through e-book services, limited research has explored how such digital integration can enhance the role of libraries as public learning spaces.

Research indicates that virtual tours improve both cognitive and affective engagement with cultural or public places while reinforcing their educational impact[14]. Furthermore, VEs facilitate social interactions that closely resemble those in physical spaces[15]. Given these insights, integrating digital tools into learning infrastructure could extend learning opportunities beyond physical constraints. This approach could attract a broader range of learners, thereby promoting educational equity. However, little research has examined which parts within LFs attract the most engagement in virtual settings. This study aims to address this gap by analyzing spatial behavior within a digitally replicated library, offering insights into the role of virtual spaces in shaping learner's experiences.

3. Materials and Methods

3-1. Learners and Learning Facilities

To analyze LFs in Daejeon City, we utilized

6) Huang, Q., Cui, X., & Ma, L., 'The Equity of Basic Educational Facilities from the Perspective of Space,' 2023, Sustainability, 15(15), p.12031.

7) Carlos, M., et al., 'Introducing the "15-Minute City": Sustainability, resilience and place identity in future post-pandemic cities,' 2021, Smart Cities, 4(1), p. 93.

8) Molina-García, J., et al., 'Different neighborhood walkability indexes for active commuting to school are necessary for urban and rural children and adolescents,' 2020, International Journal of Behavioral Nutrition and Physical Activity, 17(1), p.8.

9) Ferrer-Ortiz, C. et al., 'Barcelona under the 15-minute city lens: Mapping the accessibility and proximity potential based on pedestrian travel times,' 2022, Smart Cities, 5(1), p.154.

10) Park, S., 'Measuring public library accessibility: A case study using GIS,' 2012, Library & information science research, 34(1), p.13-21.

11) Aabø, S., Audunson, R., & Vårheim, A., 'How do public libraries function as meeting places?,' 2010, Library & Information Science Research, 32(1), p.19.

12) Given, L. M., & Leckie, G. J.,. '"Sweeping" the library: Mapping the social activity space of the public library,' 2003, Library & Information Science Research, 25(4), p.367.

13) Scott, R., 'The role of public libraries in community building,' 2011, Public Library Quarterly, 30(3), p.191.

14) Ji, F., Wang, F., & Wu, B., 'How does virtual tourism involvement impact the social education effect of cultural heritage?', 2023, Journal of Destination Marketing & Management, 28, p.100779.

15) Fiedler, M., Haruvy, E., & Li, S. X., 'Social distance in a virtual world experiment,' 2011, Games and Economic Behavior, 72(2), p.426.

four public and commercial datasets. The first two datasets[16)17)] from government' public data portal provided geolocations and enrollment data for 788 LFs, including 150 elementary schools, 88 middle schools, 62 high schools, 94 libraries, and 354 academies. The third dataset[18)] from the data portal detailed libraries' locations, book collections, and land areas, offering information of their scales and spatial distribution. Lastly, mobile phone data[19)], which were collected by SK Telecom in 2022 and are commercially available, was utilized. This data allowed us to analyze adolescent (ages 0-19) mobility in relation to LFs. By integrating these datasets, we examined both spatial accessibility and usage patterns within the local LF network.

3-2. Network of Learning Facilities

A proximity-based spatial network was constructed using the mobile phone dataset, following the network generation method introduced in a previous study[20)]. The procedure for network construction is as follows:

- LFs and coverage cells, which are determined in the mobile data, serve as network nodes.
- The straight-line distance between LFs and coverage cells was calculated using Haversine to identify node pairs within a 1 km radius. Nodes were filtered based on walking distance, ensuring that only those reachable within one minute (at a walking speed of 4 km/h) were linked. The walking distance was measured using the Kakao Map API.
- Link weights were set by the average mobile population of adolescent within the administrative district of the coverage cell.
- This bipartite spatial graph was then projected into a one-mode network to establish direct LF-to-LF connections.

The structure of the LF-to-LF network was analyze to assess relative significance of each LF within the network. Centrality measures such as degree centrality, Eigenvector centrality, and betweenness centrality were utilized.

3.3 Behavior Data within Virtual Testbed

Sintanjin Library was replicated on a virtual testbed (Fig. 1), which was previously reported in detail[21)]. We implemented the exterior of the real library site with Non-Player Characters (NPCs) of learners and featured objects such as a book return slot. The environment was developed using Minecraft, a popular platform enabling spatial exploration through avatars, ensuring many adolescents' familiarity with the platform.

Behavior data of virtual visitors within Sintanjin Library was collected. Participants were recruited through online Minecraft communities. They received detailed instructions outlining the study's objectives, participation guidelines, and control mechanisms. They freely explored the virtual space, after which they completed surveys assessing their intention to visit the physical site before and after the virtual visit. After the exploration, they submitted one of the impressive screenshots they have captured. Also, our server automatically stored logs of every avatar's

16) Korean Public Data Portal (공공데이터포털), 전국초중등학교위치표준데이터, (2025.02.28.) www.data.go.kr/data/15021148/standard.do

17) Korean Public Data Portal (공공데이터포털), 전국학원및교습소표준데이터, (2025.02.28.) www.data.go.kr/data/15096277/standard.do

18) Korean Public Data Portal (공공데이터포털), 전국도서관표준데이터, (2025.02.28.) www.data.go.kr/data/15013109/standard.do

19) Korea Data Exchange (KDX), 대전광역시 유동인구 (22년도), (2025.02.28.) kdx.kr/data/view/37680

20) Chang, M., Lee, G., & Lee, J. H., 'Analysis of urban visitor walkability based on mobile data: The case of Daejeon, Korea,' 2023a, Cities, 143, p.104564.

21) Chang, M. et al., 'The influence of virtual tour on urban visitor using a network approach,' 2023b, Advanced Engineering Informatics, 56, p.101025.

locations in a VE, every second. The logs contained a timestamp, participant identifier, and 3-dimensional coordinate of avatar's position.

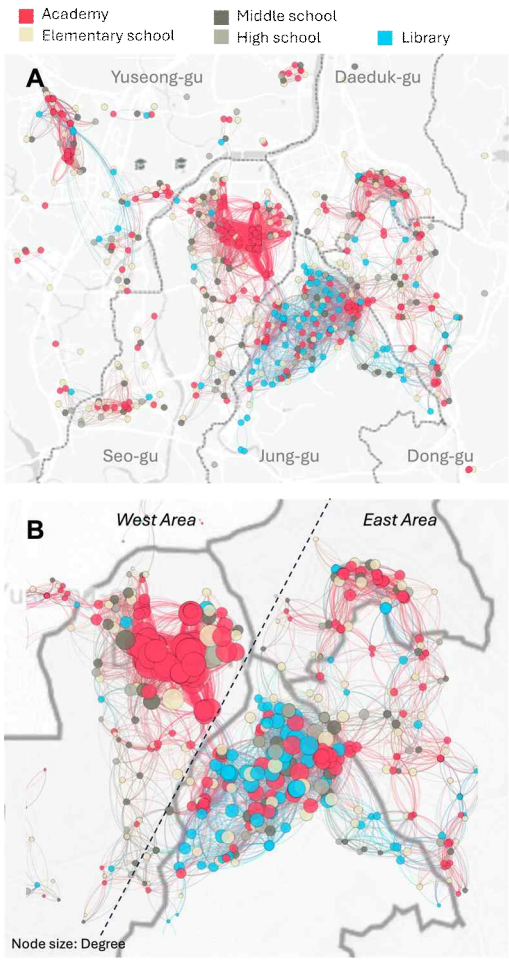
[Fig. 1] Public library reproduced in Mincraft. (A) Real environment. (B) Virtual environment.

4. Results and Discussions

4-1. Network of Learning Facilities

In this section, we described the results of the network analysis based on walkability and mobile phone population. As for an overview of the spatial distribution of LFs in five boroughs, academies dominated the areas of LFs in the western district (Fig. 2A), while fragmented learning communities appeared in Seo-gu and Yuseong-gu. In the western district, large groups of academies existed, but few libraries were located. Yuseong-gu had the largest portion of academies compared to the other types of LFs, and several LFs were isolated from communities. While various classes of LF appeared in Jung-gu, libraries were widely distributed across the area. Daedeok-gu had more academies than libraries and fragmented groups of LFs. In Dong-gu, most LFs were loosely connected into a network.

The result of the degree centrality (C_d) analysis showed two different groups of LFs: academies and mixed LFs. We detected the nodes with high C_d in two areas: densely connected academy streets in Seo-gu and a dense area of libraries in Jung-gu (Fig. 2B). As a result of the investigation centered on C_d, we found that the group in the western district consisted of academy LFs. In contrast, the group in the eastern district consisted of a mixture of different types of LFs. Of the mixed group, overall academies, libraries, and several schools had high level of C_d.



[Fig. 2] Spatial distribution of LFs in Daejeon. (A) LFs and their spatial network projected on the map of Daejeon. (B) Degree centrality of LFs, centered on the comparison between west area and east area.

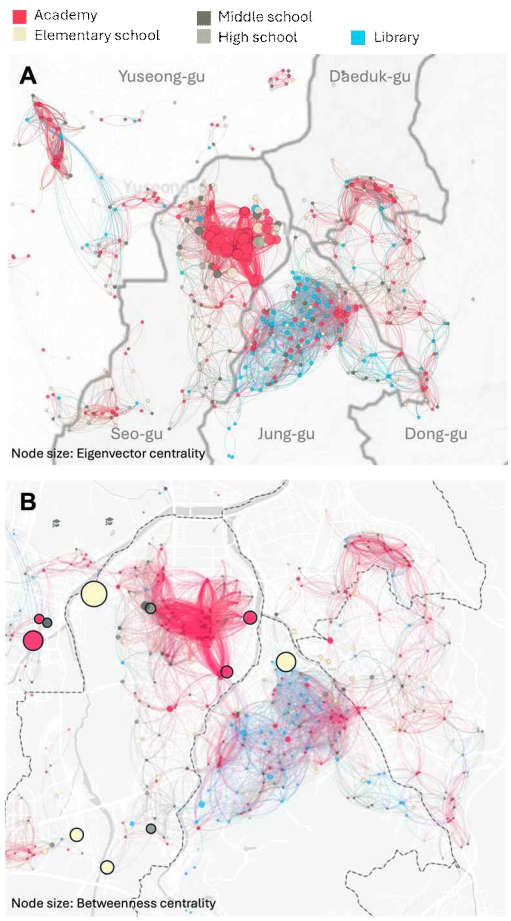
Daejeon's metropolitan area was divided into the western districts (Yuseong-gu and Seo-gu) and the eastern districts (Dong-gu, Jung-gu, and Daedeok-gu). A big characteristic of the LF network was that there was a huge educational gap between the western and eastern districts, which has been a problem recognized at the municipality level. While there were a lot of attempts made to assuage the situation through bureaucracy, the situation has been barely improved, since the gap was inherently tied to other social gaps such as economic gap.

The western districts consisted of new towns where academies were the most significant portion of LFs. Yuseong-gu, the westernmost district has the highest concentration of graduate degree holders in the entire country. This is due to the plethora of research organizations, public corporations, and national colleges in this area. As expected, Yuseong-gu reflected the enthusiasm for education, only seconded by another western district of Seo-gu. Interestingly enough, while Yuseong-gu's educational fervor did not extend to the private educational sector (academies), Seo-gu was home to the biggest academy neighborhood in the city. This densely connected LFs was in the biggest commercial area of the new town. Another characteristic of western districts was isolated LFs in villages. This showed that LFs in the new town were unconnected to the city's network.

In contrast, the eastern districts consisted of old towns in which most LFs were connected into a giant component. The mixed types of LFs, including a plethora of libraries, were loosely connected and widely distributed in the eastern districts. Libraries were considerably concentrated in Jung-gu, where the large commercial area of old towns is located.

4-2. Hubs of Learning Facility Network

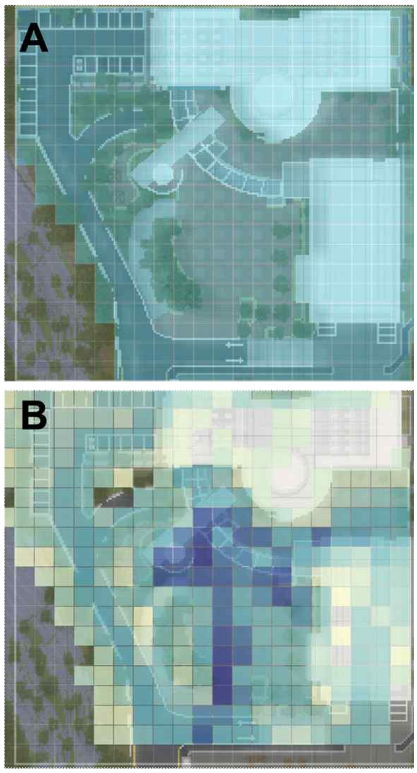
In the Eigenvector centrality (C_e) analysis, groups of academies were dominant over other types of LFs. The academy nodes of high C_e were particularly located in Seo-gu (Fig. 3A). Otherwise, the nodes, including libraries, in the east district showed remarkably decreased C_e. Also, the results of betweenness centrality (C_b) showed different patterns from C_e and C_b (Fig. 3B). Several elementary schools and academies located outside of the main groups showed the highest C_b, as indicated by thick lines in Fig 3B. These LFs were not outstood in the two centrality analysis. But the results showed that they were important connection points between local LFs. Libraries, middle schools, and high schools showed low levels of C_b.



[Fig. 3] Further centralities of LFs in Daejeon City. (A) Eigenvector centrality of LFs. (B) Betweenness centrality of LFs. The LFs with relative high centralities were highlighted with the thick line.

The C_d and C_e indicated that the center of adolescent learning activities was concentrated in the western academy streets and surrounding schools. As C_e showed, many academies in the west district were located within a distance of 1 km (15 minutes on foot) of each other. Also, there was a large floating population of children and teenagers moving between the academies. The highest levels of C_b were mainly found in schools, as analogous to the previous work[22], which observed that residential land use is formed with high C_b on the city's outskirts, whereas commercial land use is concentrated near the city's center.

We initially hypothesized libraries would function as hubs within the network. While libraries were widely distributed in the eastern district, and a major library was located on the main street, they did not served as hubs. Their accessibility to other LFs and actual use from adolescents were lower than academies. Based on these results, a large public library named as Sintanjin Library was selected as a representative LF because it was a isolated component in the eastern district and had low centralities. The library had 156K books, 1.2K seats, 8,809 km^2 of land, and 162 Instagram posts (relatively low).



[Fig. 4] Weighted Degree Projection on the Map of Virtual Library. (A) Spatial network[23] based on participant logs within the library. Nodes were projected on the map as blue squares. (B) Weighted-degree of nodes. Yellow color indicates relatively low weighed degrees and dark blue color indicates relatively high weighted degrees.

4-3. Spatial Experience in Virtual Library

Of 99 participants who visited the virtual library, 24.2% were residents of Daejeon, and 75.8% were not. The spatial diffusion of the participants was found centered on the library square. Fig. 4A showed the spatial network of the Sintanjin library. The highest weighted degrees of the nodes were the entrance to the library square, the leftside of the square, the area around a book return slot, the rooftop, and the stairs to the rooftop (Fig. 4B).

The results of photos taken from the participants were displayed in Table 1. The square, building, avatars, and return slot were taken in the photos. Table 1 describes the count of subjects taken in the images. The most dominant subject was the library building and square (90.91%). Avatars of Non-Player Characters were captured in the images with a high proportion (51.52%), while participants captured themselves in only 10-25% of photos. The representative object of libraries, a book return slot, was shown in 48.48% of photos,

22) Wang, S., Xu, G., & Guo, Q., 'Street Centralities and Land Use Intensities Based on Points of Interest (POI) in Shenzhen, China,' 2018, ISPRS International Journal of Geo-Information, 7(11), p.425.

23) Lee, G. et al., 'Perception graph for representing visuospatial behavior in virtual environments: A case study for Daejeon City,' 2024, Advanced Engineering Informatics, 62, p.102594.

and a close-up of the return slot was 9.09%. We compared the intention to visit the Sintanjin library, gathered by surveys before and after the virtual visit. The intention to visit increased by an average of 1.21 on a 7-point scale.

[Table 1] Objects captured in participants' photos. Each participant submitted one best photo, and 33 among them were taken within the library.

Object	Count (Ratio)
Building & Square	30 (90.91%)
Return slot	16 (48.48%)
Return slot (close-up)	3 (9.09%)
Avatar (self)	8 (24.24%)
Avatars (others)	3 (9.09%)
Avatars (NPCs)	17 (51.52%)

Some notable areas were found common in the logs and images. The areas were the entrance, the square, and the front of the return slot (Fig. 5). The logs and images close to the return slot showed such representative objects are related to the sense of place of libraries. The logs have added details to participant behaviors. As Fig. 4B shows, most participants passed the square through the left side cells where the avatars of Non-Player Characters were located. Also, participants used the stairs to the building rooftop and explored the rooftop. Participants appeared to casually the behaviors unnatural in the physical environment (such as observing people or climbing the long stairs).

In summary, we implemented the exterior of the actual library in a VE. Building on previous studies that provided library content using e-book services, this investigation covers a brief introduction to spatial behaviors of remote visitors in the virtual library environment. The selfie photos in front of the building illustrated private experiences in the virtual library. Contact with other avatars in the square substantiated the use of the virtual library as a public space.

[Fig. 5] Representative photos within virtual library.

5. Conclusion

As a case study of Daejeon in South Korea, this study contributed to understanding land use in terms of Learning Facilities (LF) and revealing their connectivity. The degree centrality revealed patterns within LF distributions in each district. The facilities with high Eigenvector centrality were concentrated in academy streets, while the facilities with high betweenness centrality mainly consisted of elementary schools on the outskirts of major groups. Such centrality analysis can help administrators plan LFs for bridging the educational gaps between the areas. Despite these findings, educational disparity stems from broader socioeconomic and institutional factors. Future work should incorporate multivariate analyses to account for these complexities. Also, the practical applicability of these findings in policy implementation should be studied.

This study tested an extension of prior works that have provided book resources on cyberspace. We shared the participants' early feedback on the virtual visits by implementing the library spaces in a virtual environment (VE). However, the VE implementation covered only the building exterior and outdoor site. Future work can explore

learner behaviors inside library and gain deeper insights into the utilization of LFs in VE.

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