Long-Term Memory Organization and Dynamics

Preeti Vijayakumar
Human Factors in Information Design, Bentley University

HF 700: Foundations in Human Factors

Dr. William Gribbons

April 1, 2024

Long-Term Memory Organization and Dynamics

Humans, like many other species, are ‘anticipatory systems’. We construct predictive models of ourselves and our environment, allowing us to quickly and robustly make sense of incoming data (de Lange et al, 2018). Our subjective experience reflects not only sensory information (bottom-up processing) from the environment but also our prior knowledge or expectations (top-down processing). A remarkable feature of the brain is its ability to integrate these two sources of information seamlessly in a dynamic and rapidly changing environment (Sohoglu, 2012). This paper explores the organized, interconnected and dynamic nature of long-term memory, the effect of prior knowledge on perception, and the contrasting knowledge structures and cognitive processes underlying novice and expert performance.

Long-Term Memory (LTM)

Long-term memory (LTM) refers to the memory system that allows us to store and retrieve information for an extended period, often even a lifetime (Adams, 1980). The capacity of LTM is almost infinite. LTM can be fractioned into *explicit* (or *declarative*) memory, where information about environments is coded and retrieved consciously, and *implicit* (or *non-declarative/procedural*) memory, where the stimuli are processed unconsciously (Tulving, 1972; Alexandrov, 2012). Explicit memories can split into *semantic* memories of facts and relationships, and *episodic* memories of events and incidents (Alexandrov, 2012). Three primary aspects of the memory system are *encoding*, the processes whereby information is registered; *storage*, the maintenance of information over time; and *retrieval*, which refers to accessing the information by recognition, recall, or implicitly (Baddeley,1990). Knowledge in the LTM can be retrieved within milliseconds, which indicates that it is highly organized and intricately interconnected.

Building Blocks of Knowledge

Schemas

Originally introduced by Bartlett (1932), schemas are conceived of as long-term knowledge structures that people use to interpret and make predictions about the world around them. A schema allows for the encoding, storage, and retrieval of information related to particular domains (Alba & Hasher, 1983). They hold information about *concepts* which are basic categories, *attributes* which are characteristics associated with a concept, and *relationships* between concepts (Tesser and Shwarz, 2007). They help us make sense of new experiences, guide our expectations, and predict situations (Tesser and Shwarz, 2007). When schemas are inadequate, new ones are created. As we encounter new concepts, we *recall* older schemas. We identify core features that *differentiate* the new concept from the older schemas. Once a relationship is established, we use prior knowledge from the older schemas to *fill in missing information* in the new schemas. Schemas related to social groups can lead to stereotypes and biases (Schacter, 2012). Schema structures in novices are initially incomplete, and assumptions and biases are added to fill in the holes. With improvement in levels of expertise, schemas grow larger and are more accurately tuned.

Mental models

Norman (1986) defines mental models as, "an internal representation of a target system that provides predictive and explanatory power to the operator". They are constructed by individuals based on their unique life experiences, perceptions, and understandings of the world. The models are neither complete nor accurate, but they guide much of human behavior by interacting with the world and making decisions (Craik 1943; Johnson-Laird 1983; Norman, 1983). Because of cognitive limitations, it is neither possible nor desirable to represent every detail that may be found in reality. Mental models thus play a role in filtering incoming information. (Jones et al, 2011).

The theory of *'confirmation bias'* (Klayman and Ha, 1989) suggests that people seek information that fits their current understanding of the world. People filter and reject new information according to its congruence or otherwise with their existing understandings, beliefs, and values. (Jones et al, 2011).

Mental models in novices are of limited scope, comprise inaccurate information, are focussed on surface-level details, and have limited flexibility. On the other hand, mental models in experts are rich and elaborate, focussed on underlying details, and are more flexible and adaptable. (Jones et al, 2011)

Comparisons between a Schema and a Mental Model

A schema is broad, representing the structure of knowledge - a concept, object, or situation. Whereas, a mental model represents the function of knowledge, how things work, interact, and behave. It is more dynamic and adaptable than schemas, allowing simulation of scenarios and outcomes. Schemas and mental models are interconnected. We use existing schemas to build mental models. Mental models, in turn, can refine and expand our schemas as we learn and gain new experiences (Schacter, 2012).

Frames

A frame (Minsky, 1975) is a schema that contains knowledge about the structure of a familiar event, such as a short story. It specifies the general type of information expected in that situation and the order in which it should be encountered (Alba & Hasher, 1983). Frame theory (Minsky, 1975) asserts the importance of prior knowledge. If the structure of incoming information does not match one's knowledge, memory for that information should be adversely affected. This can occur because the structure of the incoming stimulus is deviant from the prototypical structure or because the person lacks adequate knowledge about the prototypical structure (Alba & Hasher, 1983).

Scripts

A script is very similar to a frame in that it too contains general information about particular, frequently experienced events. It also contains more specific information about the event. (Alba & Hasher, 1983).

Intricately Interconnected Knowledge

The intricately interconnected nature of knowledge in the mind is a fundamental principle in cognitive psychology. Semantic and propositional networks are fluid representations of knowledge. *Propositional* networks represent knowledge as a collection of propositions. Propositions are statements that can be true or false, typically expressed in a subject-predicate form. These propositions are then connected using logical operators (AND, OR, NOT) to form more complex knowledge structures. They are not as expressive or as computationally feasible as semantic networks (Alba & Hasher, 1983).

Semantic networks represent knowledge as a web of nodes and links, similar to connections in the brain. Nodes represent concepts or entities in the world, while links represent the relationships between them. These diverse relationships are inclusive, flexible, and scalable. The strength of the connections between concepts can vary. Stronger and shorter connections, as seen in experts, indicate a closer relationship and are activated first, having a higher probability of being processed correctly; the opposite, as seen in novices, increases the probability of errors. This interconnectedness of knowledge facilitates learning, making inferences, and problem-solving (Jones et al, 2011).

The strength of connections increases with *traumatic* concepts and *recency*, *duration,* and *frequency* of exposure to the concept (Baddeley, 1990). Priming is a phenomenon where exposure to one stimulus (prime) influences how you respond to a subsequent stimulus (target). It strengthens existing connections and creates new ones. This consequence can be positive or negative, and it often happens unconsciously.

Retrieval of Knowledge

The two principal methods of memory retrieval are recall, where the subject is required to reproduce the stimulus items, and recognition, where the subject can identify the stimulus from past experiences when prompted (Baddeley, 1990). Cognitive demand and inaccuracy are higher in recall than in recognition.

Activation

When we encounter a stimulus, the corresponding concept in our network becomes activated. The activation spreads along the connections within the network to related concepts. This is called the *Spreading Activation* model, in which we integrate the prior knowledge with the stimulus in a network fashion (Collin & Loftus, 1975). As designers, we need to ensure that our designs are as predictable as possible to avoid activating traumatic memories in our users. It has been discovered that the more a subject learns about a concept, the higher the number of facts (paths) leading from a node. This decreases the rate at which activation spreads down the path. This interference in reaction time is referred to as the *Fan Effect*, because of the fan of paths leading out of the node (Anderson, 1981). This is why overwhelming the user with information and choices would increase cognitive load and retrieval times.

Factors Affecting Retrieval

Stronger connections enforced through trauma, recency, duration, and frequency, make retrieval faster. Other contributing factors include a combination of retrieval cues like context or clues, internal state of the subject like mood, emotion, focus or attention, environmental interference, and sleep and age.

Reconstruction - Dynamic Nature of Knowledge

In congruence with schema theory, specific domain-related prior knowledge improves the acquisition of new, domain-related information. *Assimilation* refers to the process of interpreting new information or experiences within an existing schema; it strengthens the connections between related concepts. It is a function of the amount of prior relevant knowledge without which information is quickly lost.

Accommodation refers to the process of modifying existing schemas to add information or experiences that don't fit neatly into them; it creates new connections within the network. Ideally, there should be a balance between assimilation and accommodation; dissonance would lead to anxiety. With age, flexibility for assimilation and accommodation decreases, making it harder to learn (Alba & Hasher, 1983).

Basic Processes

Schema-driven encoding of complex information is characterized by four basic processes: selection, abstraction, interpretation, and integration (Cockcroft et al, 2022).

Selection. Of all the concepts in a given stimulus, only some will become part of the memory.

Abstraction. Information selected because it is important and/or relevant to the schema is further reduced. This process codes the meaning but not the format of a message.

Interpretation. The encoding deficit that results from selection and abstraction is compensated for at recall by reconstruction. Distortions occur because those semantic propositions that are encoded are actually interpretations of the explicitly presented information perceiver's activated schema. Such errors are often referred to as constructive errors because they involve the addition of information to the memory representation of a complex event (Alba & Hasher, 1983).

Integration. A single integrated memory representation is created from whatever accurate information is selected, whatever interpretations are drawn, and whatever general knowledge exists that is relevant to the stimulus. Integration processes are thought to occur at two different stages of memory: (a) when a new schema is formed and (b) when an existing schema is modified (Cockcroft et al, 2022).
New information is immediately integrated into the prior knowledge system that subjects possess about the topics, resulting in an inseparable combination of the new and old information. Once integration occurs and old knowledge has been altered or updated, accurate retrieval of actually presented information becomes highly unlikely. New information will be integrated into old knowledge structures (Sommer, 2022).

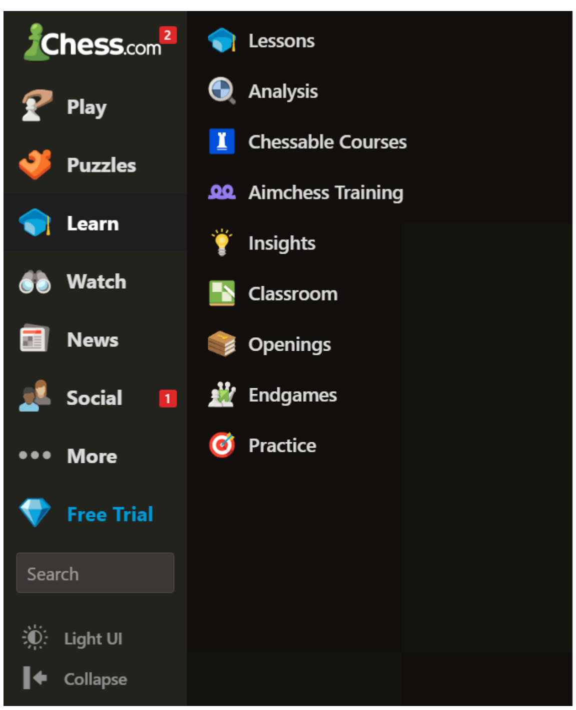
Design review: An online chess platform

Chess.com is a popular online chess platform that offers a variety of features for players of all skill levels. In this example, we will consider a Novice to be a beginner player trying to learn chess for the first time, and an Expert to be an experienced player who has mastered the game of chess.

Figure 1: Layout of the online board game.

Expertise

Results show that mental models may be powerful descriptors of a player. When the Expert sees a chess position in a game, they can recognize such familiar patterns. They can then associate these patterns with prior knowledge of moves stored in their memory, that have proven to be good moves in the past. Novices do not have enough exposure to game configurations to have developed many of these kinds of patterns. Hence they deal with the board in a piece-by-piece manner (Feltovich et al, 2006). To support novices, the platform offers learning resources and post-game analysis.



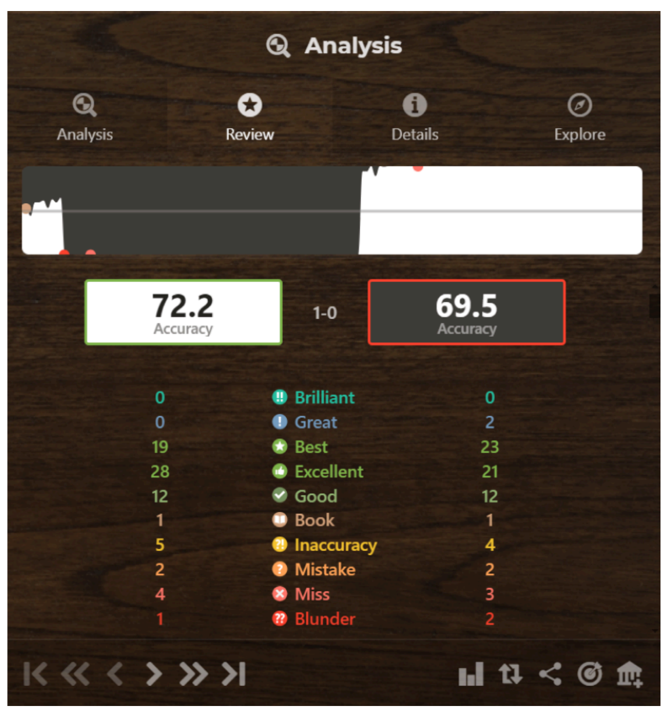


Figure 2: Learning resources (for novices) and analysis tools (for players of all levels of expertise).

Tasks

The principle goal of a game of chess is to checkmate the opponents's king. This involves user tasks such as selecting a piece to move, choosing a valid destination square based on chess rules and piece movement capabilities, considering the opponent's moves and plan strategy, and utilizing chess tactics and strategies to gain an advantage. The Expert's mental model includes all this information with strong connections because of the frequency of their chess matches. The Novice has just assimilated this and has not played enough games to strengthen connections. Features to reduce anxiety on the Novice:

(1) *Selecting player level with 5 options* - By default, the player is set to a beginner-level game with the computer. Should the Expert want to switch levels or play with an actual opponent from around the world, the options are available on the screen.

(2) *Highlighting possible moves*- By default, possible moves are highlighted; the system does not even let a player make a move that may end in a Check. This makes it easier for the Novice to correct their mistake and continue the game. The Expert can turn off this feature in the settings.

(3) *Setting duration* - By default, the player can take any length of time to make a move, but should the Expert want to set durations, they can do so in the settings.

Figure 3: Tasks - Features offered: changing levels, viewing possible moves, setting time.

Affordances & metaphors

In screen displays, principles of affordance include following conventional usage of images and the allowable interactions, and using words to describe the action (Norman, 1986). Here, the Novice can see the metaphor of a physical chess board on their screen digitally. Although it is not evident which piece represents which role immediately, they have designed the pieces to look similar to the physical pieces, which themselves are metaphors for the roles they represent (eg: the horse represents the knight, the piece with the crown represents the queen). Players of any expertise level can understand the online board and can choose more realistic themes if they want to.

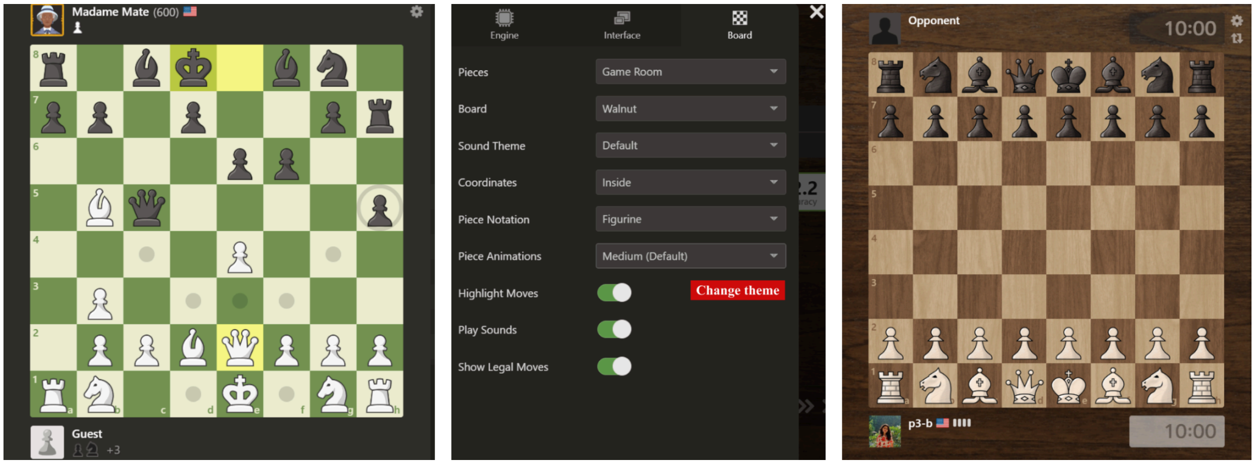
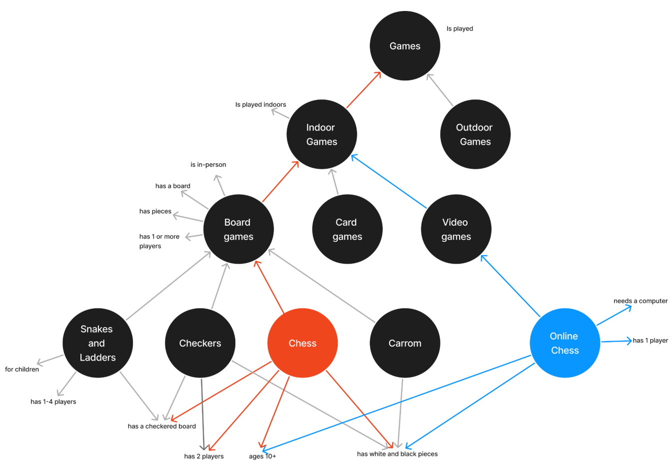


Figure 4: Changing themes of board and pieces to make them look more realistic or conventional.

Categorization



In a classical model, chess as a game would satisfy the rules of a board game. It has features similar to Checkers and Snakes & Ladders in that they all have checkered boards. Checkers and chess are 2-player games. It is also similar to Carrom in that there are white and black pieces to be moved across a board. These different types of relationships with other games would make it easier to assimilate Chess into the schema of board games.

Figure 5: Classical semantic network for Chess and Online Chess

Online chess, however, could instead be categorized as a one-player video game. Overall, both versions could be assimilated within the schema for indoor games.

Conclusion

Understanding long-term memory as organized, interconnected, and dynamic informs how we structure information for easy retrieval, personalize learning based on existing knowledge networks, and create effective experiences by strengthening connections through exposure and repetition. By considering how memory works, we can design user interfaces that feel intuitive, promote knowledge retention, and cater to individual needs.

References

Adams, J. A. (1980). *Learning and Memory, an Introduction*.

Alba, J. W., & Hasher, L. (1983). Is memory schematic?. *Psychological Bulletin*, *93*(2), 203.

Alexandrov, A. K., & Fedoseev, L. M. (2012). *Long-term Memory*.

Anderson, J. R. (1981). Effects of prior knowledge on memory for new information. *Memory & Cognition*, *9*(3), 237–246. https://doi.org/10.3758/bf03196958

Baddeley, A. (1990). *Human memory : theory and practice*. Psychology Press.

Bartlett, F. C. (1932). Remembering: A study in experimental and social psychology. *British Journal of Educational Psychology*, *3*(2), 187–192. https://doi.org/10.1111/j.2044-8279.1933.tb02913.x

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, *82*(6), 407–428. https://doi.org/10.1037/0033-295x.82.6.407

Craik, K. The narure of explanarion. Cambridge: Cambridge University Press, 1943.

Cockcroft, J. P., Berens, S. C., Gaskell, M. G., & Horner, A. J. (2022). Schematic information influences memory and generalisation behaviour for schema-relevant and-irrelevant information. *Cognition*, 227, 105203.

de Lange, F. P., Heilbron, M., & Kok, P. (2018). How Do Expectations Shape Perception? *Trends in Cognitive Sciences*, *22*(9), 764–779. https://doi.org/10.1016/j.tics.2018.06.002

Feltovich, P. J., Prietula, M. J., & Ericsson, K. A. (2006). Studies of expertise from psychological perspectives. *The Cambridge handbook of expertise and expert performance*, 41-67.

Johnson-Laird, P. N. (1980). Mental Models in Cognitive Science. *Cognitive Science*, *4*(1), 71–115. https://doi.org/10.1207/s15516709cog0401_4

Jones, N. A., Ross, H., Lynam, T., Perez, P., & Leitch, A. (2011). Mental models: an interdisciplinary synthesis of theory and methods. *Ecology and society*, *16*(1).

Klayman, J., & Ha, Y. (1989). Hypothesis testing in rule discovery: Strategy, structure, and content. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(4), 596–604. https://doi.org/10.1037/0278-7393.15.4.596

Norman, D. A. (1986). Cognitive engineering. *User centered system design*, *31*(61), 2.

Norman, D. A. (2014). Some observations on mental models. In *Mental models* (pp. 15-22). Psychology Press.

Schacter, D. L. (2012). Adaptive constructive processes and the future of memory. *American Psychologist*, *67*(8), 603.

Sohoglu, E., Peelle, J. E., Carlyon, R. P., & Davis, M. H. (2012). Predictive Top-Down Integration of Prior Knowledge during Speech Perception. *Journal of Neuroscience*, *32*(25), 8443–8453. https://doi.org/10.1523/jneurosci.5069-11.2012

Sommer, T., Hennies, N., Lewis, P. A., & Alink, A. (2022). The assimilation of novel information into schemata and its efficient consolidation. *Journal of Neuroscience*, *42*(30), 5916-5929.

Tesser, A., & Schwarz, N. (2007). *Blackwell Handbook of Social Psychology : Intraindividual Processes*. John Wiley & Sons.

Tulving, E. (1972). Episodic and semantic memory. *Organization of memory*, *1*(381-403), 1.