NeverMind

An Interface for Human Memory Augmentation

by

Oscar Rosello
B.Arch, M.Arch, Universitat Politecnica de Catalunya, 2012

Submitted to the Department of Architecture and the Department of Electrical Engineering & Computer Science in Partial Fulfillment of the Requirements for the Degrees
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Abstract

If we are to understand human-level intelligence, we need to understand how memories are encoded, stored and retrieved. In this thesis, I take a step towards that understanding by focusing on a high-level interpretation of the relationship between episodic memory formation and spatial navigation. On the basis of the biologically inspired process, I focus on the implementation of NeverMind, an augmented reality (AR) interface designed to help people memorize effectively. Early experiments conducted with a prototype of NeverMind suggest that the long-term memory recall accuracy of sequences of items is nearly tripled compared to paper-based memorization tasks.

For this thesis, I suggest that we can trigger episodic memory for tasks that we normally associate with semantic memory, by using interfaces to passively stimulate the hippocampus, the entorhinal cortex, and the neocortex. Inspired by the methods currently used by memory champions, NeverMind facilitates memory encoding by engaging in hippocampal activation and promoting task-specific neural firing. NeverMind pairs spatial navigation with visual cues to make memorization tasks effective and enjoyable.

The contributions of this thesis are twofold: first, I developed NeverMind, a tool to facilitate memorization through a single exposure by biasing our minds into using episodic memory. When studying, we tend to use semantic memory and encoding through repetition; however, by using augmented reality interfaces we can manipulate how our brain encodes information and memorize long term content with a single exposure, making a memory champion technique accessible to anyone. Second, I provide an open-source platform for researchers to conduct high-level experiments on episodic memory and spatial navigation. In this thesis I suggest that digital user interfaces can be used as a tool to gather insights on how human memory works.

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NEVERMIND: AN INTERFACE FOR HUMAN MEMORY AUGMENTATION

SM in Architecture Studies: Design and Computation and SM Elecrical Engineering & Computer Science, June 2017

Contents

"For just as in a person with a trained memory, a memory of things themselves is immediately caused by the mere mention of their places, so these habits too will make a man readier in reasoning, because he has his premises classified before his mind's eye, each under its number." aristotle, topica, 163, 24-30

Background: Interfaces for Memory Augmentation

If we are to understand human-level intelligence, we need to understand how memories are encoded, stored and retrieved. I take a step towards that understanding by focusing on the relationship between memory formation and spatial navigation. On the basis of a biologically inspired process, I designed NeverMind, an augmented reality interface conceived to help people memorize effectively. Early experiments conducted with a prototype of NeverMind suggest that the long-term memory recall accuracy of sequences of items is nearly tripled compared to paper-based memorization tasks. This work aspires to contribute to the fields of human-computer interaction, human and artificial intelligence and the learning sciences.

Vision: A Human Memory Augmentation Interface

In the course of this thesis, I suggest that we can trigger episodic memory for tasks that we normally associate with semantic memory, by using interfaces to passively stimulate the hippocampus, the entorhinal cortex, and the neocortex. Inspired by one of the most popular methods used by memory champions, [1] NeverMind facilitates memory encoding by engaging in hippocampal activation and promoting task-specific neural firing. NeverMind pairs spatial navigation with visual cues to make memorization tasks more enjoyable and effective.

[1] Foer, J. (2012). *Moonwalking with Einstein: The Art and Science of Remembering Everything*. Penguin Books, New York, reprint edition edition

The original concept for this thesis derives from my work in Patrick Winston's 2016 edition of the 6.833 The Human Intelligence Enterprise class and Pattie Maes' 2016 edition of MAS S60: Human-Machine Symbiosis class. Early work on NeverMind [2] was presented at the Association for Computing Machinery (ACM) User Interface and Software Technology (UIST) Conference in Tokyo, Japan in October 2016 and was granted the Best Poster Award.

[2] Rosello, O., Exposito, M., and Maes, P. (2016). NeverMind: Using Augmented Reality for Memorization. pages 215–216. ACM Press

Objectives: Single-Shot Memorization and Open-Source Platform

THE OBJECTIVE OF THIS THESIS is twofold. First, to present NeverMind, a digital tool in a single shot possible. By passively engaging our perceptual system into using episodic memory, users are able to form lasting memories with just a short 3-second exposure of the target content to memorize. In general, when studying, we tend to use semantic memory and encode through repetition, however, by using interfaces there is an opportunity to manipulate the way our brain encodes information and form lasting memories with a single exposure.

NeverMind as a Memorization Tool

Partial motivation for this thesis is to use technology to change the way students memorize. From an early age, it has been drilled into us: memorization is about repetition [3]. We are told to repeat inside our heads the study material, confining ourselves to solitary study areas.

[3] Carey, B. (2015). *How we learn: the surprising truth about when, where and why it happens*. Random House. OCLC: 911018415

In school, we are taught that in order to retain information we should read information over many times until the content is imprinted in our brain. In fact, repetition is one of the most familiar learning methods for students: Everyone has memorized facts or vocabulary words by repeating them until the content sticks.

However, there are more effective and enjoyable study methods that are in line with the way our brain encodes, stores and retrieves information. For this thesis, I plan to develop such a method, using interface design as an approach to facilitate memorization.

My intention is not to suggest that memorization should be the basis for education or learning, but to acknowledge that a part of learning involves memorization and this experience can be eased using technology.

NeverMind as a Research Tool

The second goal of this thesis is to show how NeverMind can be used as an open-source platform for studying memory from a cognitive perspective. I suggest digital interfaces can play a major role as a non-invasive study tool to facilitate our understanding of episodic memory and facilitate our understanding of the relationship between spatial navigation from a high-level view.

Episodic memory is a type of long term memory that relates to events and personal experience. It’s the mechanism that allows us to answer autobiographical statements; that is, answer the questions to *where* and *when*. For example, when we think about what we ate yesterday for dinner, we remember *what* we ate, but also *where* we ate it and *when* we ate it. There is always a spatial and temporal component associated to that memory. This process is very different from semantic memory, which is the mechanism we use when recalling facts. For example, when recalling what the capital of Spain is. When we try to consciously memorize information, we tend to use semantic memory and repetition as the way to encode it.

Understanding the mental processes involved in spatial navigation and memory are still a current challenge for researchers[4]. The two most popular approaches for studying spatial navigation are either using animal subjects or using functional magnetic resonance imaging (fMRI) combined with virtual reality. Although both approaches have revealed important insights on many aspects of spatial navigation, these techniques don't involve subjects moving through space and offer a limited scope on what the human mind is doing while navigating. Because of technical limitations of current fMRI methods it's not possible to perform brain scans while subjects are moving in space.

[4] Taube, J. S., Valerio, S., and Yoder, R. M. (2013). Is Navigation in Virtual Reality with fMRI Really Navigation? *Journal of Cognitive Neuroscience*, 25(7):1008–1019

In the case of animal subjects, recording electrophysiological signals in rodents has contributed to uncovering many of the processes involved in navigation and memory. Research using rodents [5] has repeatedly shown the important role that active movement plays in navigation. Single unit recordings have found various cell types that respond to different spatial aspects of an animal's environment, but for technical or ethical reasons similar experiments haven't been performed in human subjects.

[5] O'Keefe, J. and Nadel, L. (1978). *The hippocampus as a cognitive map*. Clarendon Press ; Oxford University Press, Oxford : New York

Figure 1: A microdrive array housing six independently adjustable four-channel tetrodes is affixed to the skull of the mouse, directly above the hippocampus, allowing large numbers of individual cells to be recorded during behavior. Credit: Wilson, et al., "Impaired Hippocampal Representation of Space in CA1-Specific NMDAR1 Knockout Mice,"

Another current approach for studing spatial naviation and memory is combining fMRI with virtual reality. The advantage of using virtual reality (VR) is the possibility to simulate highly realistic environments while the subject is performing an fMRI scan. Usage of VR and real-time fMRI offers great potential to identify underlying cognitive mechanisms such as spatial navigation and episodic memory [6].

[6] Mueller, C., Luehrs, M., Baecke, S., Adolf, D., Luetzkendorf, R., Luchtmann, M., and Bernarding, J. (2012). Building virtual reality fMRI paradigms: A framework for presenting immersive virtual environments. *Journal of Neuroscience Methods*, 209(2):290–298

Experiments such as the CityMap experiment (Mueller et al., 2012), reveal hippocampal activation during memory retrieval in spatial navigation tasks. However, in the case of using fMRI and virtual reality, there are clear differences between the spatial systems that are activated in virtual reality navigation tasks and the systems activated during real-world navigation: "virtual navigation differs from real navigation, which relies heavily on motor, proprioceptive, and vestibular information-none of which are activated when a participant is lying supine in a functional imaging scanner while performing a virtual reality navigational task. One's sense of spatial orientation depends on proprioceptive feedback and motor, which inform the participants about their body movements, and vestibular signals, which provide information about head position and movement through space"[7].

[7] Taube, J. S., Valerio, S., and Yoder, R. M. (2013). Is Navigation in Virtual Reality with fMRI Really Navigation? *Journal of Cognitive Neuroscience*, 25(7):1008–1019

Because of this technical limitations I suggest there is an opportunity for digital interfaces to play a key role in identifying the mental processes involved in spatial orientation and navigation. Researchers can use interfaces as a flexible, affordable and non-invasive platform for researchers to quickly iterate and test multiple experiments on spatial memory, navigation and human intelligence at the cognitive level.

Figure 2: Results of the fixed-effects group analysis for the VR-fMRI CityMap experiment showing hippocampal activation during virual spatial navigation tasks. Credit: Mueller et al, "Building virtual reality fMRI paradigms"

Organization of the Thesis

In this thesis, I will present background work on human-computer interaction related to augmentation and use it in favor of enhancing memory. Next, I will talk about the memory palace technique, an ancient method used by superior memorizers that I use as an inspiration for memory augmentation. Then, I will describe the details of NeverMind, an interface designed to support human memory. Following, I will describe a set of experiments conducted to test the interface followed by an analysis of the experimental data and results. After that, in the discussion section, I will describe the NeverMind interface and its relationship to memory and spatial navigation from both an artificial intelligence and neuroscience perspective. Lastly, I will expose the anticipated contributions to human-computer interaction, human and artificial intelligence, learning sciences and architecture.

Memory Augmentation is Not New

Memory is one of the core components of human cognition. We use memory for everyday functioning, for learning new information and remembering the past. The sense of self is defined, in part, by one's ability to remember past events. In this sense, we are what we remember.

More so, the function of memory is not only about recalling past events or consolidating knowledge but also to allow us to plan for the future [8]. Because memory is such a fundamental component of human intelligence, the desire to augment human memory has been a topic of long interest that is still relevant today. Some recent examples to approaches to increasing human long-term memory include brain stimulation, smart drugs or external aids.

[8] Schacter, D. L., Addis, D. R., and Buckner, R. L. (2007). Remembering the past to imagine the future: the prospective brain. *Nature Reviews Neuroscience*, 8(9):657–661

However, memory augmentation is not a new idea. In fact, we have been using interfaces to augment our minds for a long time, in an attempt to increase our ability to retain information. By externalizing information, we can process more content than what our brain can handle alone.

Painting on Caves to Record the Environment

One of the first examples of externalizing our memories dates back to more than 35,000 years ago when the first modern humans started decorating caves. These paintings now serve as examples of early human symbolic behavior [9]. Such paintings recorded in detail many aspects of the environment, including weather, ground conditions and the presence of a particular species. The meaning of such paintings has remained a controversial topic for long, but one theory suggests that cave paintings were an attempt to record and preserve knowledge. Using drawings, people documented the animal species and resources available in a particular region [10] serving as a primitive encyclopedia. In a way, early cave paintings were an early version of today's cloud storage.

[9] Pike, A. W. G., Hoffmann, D. L., Garcia-Diez, M., Pettitt, P. B., Alcolea, J., Balbin, R. D., Gonzalez-Sainz, C., Heras, C. d. l., Lasheras, J. A., Montes, R., and Zilhao, J. (2012). U-Series Dating of Paleolithic Art in 11 Caves in Spain. *Science*, 336(6087):1409–1413

[10] Mithen, S. J. (1988). Looking and Learning: Upper Palaeolithic Art and Information Gathering. *World Archaeology*, 19(3):297–327

Managing Book-Keeping With Artifacts

Even the earliest known form of writing emerged from the need to enhance human memory, in the context of record keeping and maintaining historical records. "Around 4,000 B.C., the complexity of trade and administration outgrew the power of memory, and writing became a more dependable method of recording and presenting transactions in a permanent form." [11] A primitive form of writing first appeared from two sites in Zagros, a region in Iran, from an evolved system of counting using small clay tokens used for book keeping [12]. These clay tokens facilitated the offloading of a cognitive load and allowed for externalization of memory, in this case in the context of transactions, into an external physical object.

[11] Williams, L. (2012). *Kind Regards: The Lost Art of Letter Writing*. Michael O'Mara Books. Google-Books-ID: 9TDdAgAAQBAJ

[12] Schmandt-Besserat, D. (1986). The Origins of Writing: An Archaeologist's Perspective. *Written Communication*, 3(1):31–45

Enhancing Memory Using Knots

Other perhaps less known artifacts include the talking knots or khipus, a textile object used by the Incas for bureaucratic recording and as a communication device to send messages throughout their empire. Their origin dates back to 3,000 B.C. and to this day, khipus have puzzled scholars; no one has been able to decipher completely their content [13]. Khipus are textile devices made from cotton cords, arranged in such a way that there is one main cord, from which many pendant ropes with knots hang. There has been speculation

Figure 3: Quipus, or talking knots, were ancient devices made from string used by the Incas to communicate information. Credit: http://www.loscuentosinfantiles.com/los-incas-y-la-educacion-de-los-ninos

[13] Mann, C. C. (2003). Cracking the khipu code. *Science*, 300(5626):1650–1651

about khipus being ciphered in a binary system or a form of writing, but no coherent theories have yet been found. Others maintain that the khipu were mnemonic devices, "personalized visual and tactile cues for the recall of the information retained in the memory of the maker. If that was the case, the khipu would not be a form of writing because they would have been understood only by their makers, or someone familiar with the same memorized accounts or narrative.[14]"

[14] Wilford, J. N. (2003). String, and Knot, Theory of Inca Writing. *The New York Times*

The Printing Press Mechanizes Memory

Before the printing press, the main way of knowledge transfer was word to mouth; and human memory was the primary way of storing knowledge. Books were hardly accessible and scribes often altered their content during their reproduction.

The printing press has been considered a transformer of society. "The transformation from an oral culture to a literate one reshaped consciousness" [15]. The press mechanized human memory and transformed oral culture into a literary one [16]. Once the word is printed, it remains unalterable, decreasing our dependence and need to remember.

"Mechanical printing acted as an artificial memory, as did writing, but now the memory, a communal treasure, was greatly enlarged [17]".

Two qualities distinguish the press from handwriting: the capacity to duplicate texts in large numbers and the capacity to fix and preserve texts and images over centuries (Murray, 2000). After the printing press, the use of memory for knowledge transfer became less critical, changing the way ideas are transferred.

[15] Murray, D. E. (2000). Changing Technologies, Changing Literacy. *Language Learning & Technology, 4(2)*

[16] Eisenstein, E. L. (1980). *The Printing Press as an Agent of Change: Communications and Cultural Trans.* Cambridge University Press, Cambridge

[17] McCorduck, P. (1985). *The universal machine: confessions of a technological optimist*. McGraw-Hill, New York

Human Augmentation and Computation

As we have seen in the previous section, building physical artifacts to support our memories, has been part of human history for a long time. Perhaps this ability to construct devices to offload, preserve and transfer our thoughts is one of the key characteristics of human intelligence. With the appearance of the first analog modern day computers, new possibilities for memory augmentation emerged.

Bush Inspires Future Research on Augmentation

In the 1930s, during the early days of computing at MIT, Vannevar Bush introduced the Memex project, perhaps short for memory extension: "It was the ultimate memory machine; a device that would store information associatively, keeping a record of all the interconnections between ideas - but never forget things." [18] For most of his professional life, Bush was concerned about augmenting human

[18] Barnet, B. (2013). *Memory Machines: The Evolution of Hypertext*. Anthem Press, London

memory and preserving information that might be lost to people; so, the goal of the Memex project was to provide an extended intimate supplement to human memory.[19]

Bush wanted the Memex to emulate the way the brain links data by association rather than by indexes and traditional, hierarchical storage paradigms. He envisioned the Memex to be easily accessed as "a mechanized private file and library" in the shape of a desk. Apart from being a device to aid users in memory tasks, the Memex was also intended as a tool to study the brain itself.[20]

A summary of these ideas on the Memex and memory was published in 1945 in the seminal article "As We May Think". A version of this article, published a few months later in Life magazine featured multiple illustrations showing a speculative design for the Memex and other augmentation devices. The Memex was never built, it exists only on paper, but Bush's vision on augmentation inspired many researchers in computing [21].

Bush imagined a feedback process between minds and machines: "as the human mind molds the machine, so the machine also remolds the human mind, remolding the trails of the user's brain, as one lives and works in close interconnection with a machine." [22]'

[19] Barnet, B. (2013). *Memory Machines: The Evolution of Hypertext*. Anthem Press, London

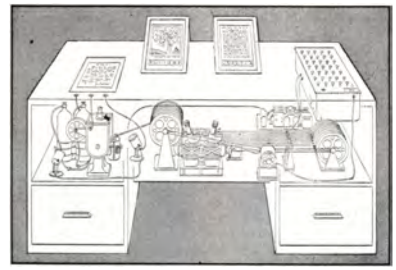

Figure 4: Concept design for the Memex that would "instantly bring material on any subject to the operator's fingertips." The operator writes notes on the reference material that is projected on the screen at left. Then the longhand notes, pictures and letters, are then filed for future reference. Credit: Time Magazine

[20] Bush, V. (2003). As We may think. *N. Wardrip-Fruin and N. Montfort, eds*

[21] Barnet, B. (2013). *Memory Machines: The Evolution of Hypertext*. Anthem Press, London

[22] Bush, V. (2003). As We may think. *N. Wardrip-Fruin and N. Montfort, eds*

Licklider Envisions A Human-Machine Symbiosis

Several years later, in his 1960, J.C.R. Licklider, at the time an associate professor at MIT, reframed Bush's vision in his article "Human-Machine Symbiosis." Licklider's hope was that people's abilities would be amplified by technical artifacts: "in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human being has ever thought" [23].

Figure 5: "A scientist of the future records experiments with a tiny camera, fitter with universal-focus lens. The small square in the eyeglass at the left sights the object." Credit: Time Magazine

[23] Licklider, J. C. R. (1960). Man-Computer Symbiosis. *IRE Transactions on Human Factors in Electronics*, HFE-1(1):4–11

Licklider's paper doesn't address the topic of memory augmentation directly, but instead offers a broader view of how humans and machines could work together. In his article, Licklider does for Augmentation what Minsky did (that same year) for A.I. with "Steps Towards Artificial Intelligence": it tells future researchers what to do.

Engelbart Starts the Augmented Human Intellect Research Center

While Licklider's "Human-Machine Symbiosis" paper told what researchers should be working on, Doug Engelbart took the first step.

In 1968, Engelbart founded the Augmented Human Intellect Research Center at Stanford; a facility dedicated to "Augmenting Human Intellect" that was working on developing and implementing a system of tools for amplifying intelligence. The goal was to increase people's problem-solving abilities using digital computers, a technology that wasn't yet available when Bush wrote "As We May Think".

Engelbart claims to have borrowed the term "intelligence amplification" from the cyberneticist W.R. Ashby. In his 1956 book "Introduction to Cybernetics", Ashby timidly writes in the last paragraph that "intellectual power, like physical power, can be amplified" and abruptly ends his book with "But this book must stop; these are not matters for an Introduction."

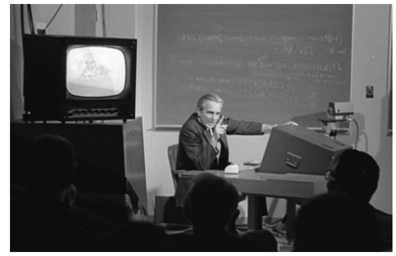

Figure 6: Screenshot of Engelbart's 1968 presentation at ACM now famously known as "the Mother of All Demos". The demo featured an array of augmentation technologies that later became the fundamentals of personal computing. These include windows, hypertext, video conferencing, the computer mouse, version control and collaborative real-time editors.

In his 1962 paper, Engelbart reflects on borrowing the term "intelligence amplification" as the slogan for his research (Engelbart, 2001): "The term (intelligence amplification) seems applicable to our goal of augmenting the human intellect in that the entity to be produced will exhibit more of what can be called intelligence than an unaided human could demonstrate; we will have amplified the intelligence of the human by organizing his intellectual capabilities into higher levels (...). In a very real sense, as represented by the steady evolution of our augmentation means, the development of 'artificial intelligence' has been going on for centuries."[24]

[24] Engelbart, D. C. (2001). Augmenting human intellect: a conceptual framework (1962). *Packer, Randall et Al. Ken. Multimedia. From Wagner to Virtual Reality. New York: WW Norton & Company*, pages 64–90

Wearable Interfaces for Augmenting Memory

The progressive increase in computational power and reduction in size has opened up many possibilities in ubiquitous computing redefining the way we interact with technology.

The First Wearables at the MIT Media Lab

In the early 1980s a group of students from the MIT Media Lab started exploring the potential of wearing their computers to campus on a daily basis. At the time, this represented a paradigm shift, as computers only interacted with their owners a small fraction of the day, because they were designed to be sitting on the desk most of the time. In contrast, the group's vision was to intimately couple the body with the machine, enabled by the reduction in weight and increase in power of computer systems. This initiative eventually led to the Wearable Computing group, an effort that spun off from Alex 'Sandy' Pentland's Human Dynamics Group.

Figure 7: The original wearables group in front of the MIT Media Lab. Credit:

Perhaps the most significant promise of wearables was getting one step closer to human augmentation, or the idea of using technology to enhance what humans alone couldn't do. Steve Mann, one of the original members of the group, and often referred as "the father of wearable computing" describes himself as the "world's first cyborg." Interestingly, one of the first applications the group worked on was on using wearables to enhance human memory.

The Remembrance Agent and Just-in-Time Information Platforms

Some of the first steps in digital memory augmentation was the development of the wearable just-in-time information platforms. These systems would bring information that is relevant to the user at a current moment and deliver it in a real-time, in an unobtrusive way. The main idea of just-in-time systems was that they were sensitive to context, collecting information from the user's location, date, time of the day, other people present or conversation topics. Then, the system would find out what a person is currently focused on and bring up notes and information that are relevant to the user.

The Remembrance Agent, a project that was part of Bradley Rhodes' Ph.D. thesis at the Media Lab[25] is one of the first examples of using a just-in-time system for memory augmentation. The project, presented in 1997, was a predecessor of the Google Glass and was designed to be used as a proactive life-logger of the information the user needed to remember. The system provides continuous background search based on contextual information based on time, location and social information. First, the system recorded the user's interactions and surrounding using cameras and microphones, then it stored the information in a database; next, it proactively retrieved potentially relevant information to the user using a small screen next to the user's eyeball.

[25] Rhodes, B. J. (2000). *Just-in-time information retrieval*. PhD thesis, Massachusetts Institute of Technology

Figure 8: Bradley Rhodes (far right) wearing the Remembrance Agent. Credit: MIT Media Lab

Pattie Maes, now director of the Fluid Interfaces Group at the MIT Media Lab, recalls using the Remembrance Agent sometime before Rhodes graduated from his Ph.D. Maes remembers how an LED embedded in the system would blink whenever there was information available. Then, the system would bring up relevant information to a particular context. Interestingly, just the sensing of the blinking cue was often enough to trigger the user's own memory.

The Memory Glasses and Subliminal Cues

Shortly after, in 2003 and also in the Wearable Computing group, Rich DeVaul presented his own prototypes for the Memory Glasses, a set of wearable devices designed to augment human memory. One of the functions of DeVaul's system was improving memory recall of people's names using subliminal cueing. Given a face, the system would display, in text and on a screen, the name of the person the user was interacting with. When using the Memory Glasses, your eye subliminally perceived the information without you being consciously aware of the information that being retrieved. A user study with 28 subjects showed a 50% increase improvement for face/name association tasks using the Memory Glasses. One key contribution of the project is noticing how people's memory recall significantly improves when using subliminal visual cues.

SenseCam and Lifelogging

More recently, in 2006, Steve Hodges and his team from Microsoft Research developed SenseCam, a personal lifelogging device designed to be worn around the user's neck. This system, an evolution of one of Steve Mann's sensor camera prototypes presented five years earlier at the Media Lab, was "designed to capture a digital record of the wearer's day, by recording a series of images and capturing a log of sensor data." The system uses sensors to detect changes in temperature, movement or lighting to start recording. Then, after the information is stored, the user can review the information in the hopes of augmenting his own memory. This system operates on the basis that human memory, unlike computer memory, is "fallible" and just-in-time information captured on the source will lead to more reliable memory recall.

Using SenseCam, Gordon Bell -also at Microsoft Research-, has been capturing his daily life as part of the MyLifeBits project. In his 2009 book, Total Recall, Bell explains how he is building his life's personal digital repository, capturing everything he has heard and seen, to be accessed with speed and ease at a later time, in an attempt to externalize and backup all his memories.

Figure 9: Microsoft SenseCam, a wearable life-logging device. Credit: Microsoft.

However, most of the projects have focused on building interfaces that monitor the user's daily life, and later lets the user retrieve the contents. Cameras record everything that the user sees and microphones to record what he hears. The focus is replacing storage and retrieval of your daily experience by a hard drive.

Now, with the emergence of wearable computing, there are new opportunities to augment human memory using digital interfaces. And to some extent, we already are relying on digital devices to store information that we need to live.

Mobile Technology and Impact on Human Memory

Today, mobile computing and the internet have enabled instant access to information. Engelbart's dream of condensing human knowledge into one location is now a reality. With a quick tap on our phone's screen we can find out the name of a restaurant that was on the tip of our tongue or bring up the details of a news article we glazed over. When faced with a tough question, often the first step we take is to use Google to search for an answer.

Increasingly, we are becoming dependent on digital devices to store many links to our memories; we can conveniently take notes, pictures, schedule events and search for information using a single object that fits in our pocket. There is a tendency for more objects or devices that we used to use as supports for our memories to be combined into a single device that is available to us at any time, anywhere. Our phones have become a prosthetic for our memory without us even realizing it.

We Remember Where but not What

A Recent article by Betsy Sparrow shows how having information available at our fingertips at any time is cognitively affecting of our brain. Our ability to recall content from memory has decreased, making our minds less plastic. The "processes of human memory are adapting to the advent of new computing and communication technology." In experiments, Sparrow shows some aspects of how having information available shapes our memory: "people forget items they think will be available externally and remember items they think will not be available"[26].

[26] Sparrow, B., Liu, J., and Wegner, D. M. (2011). Google Effects on Memory: Cognitive Consequences of Having Information at Our Fingertips. *Science*, 333(6043):776–778

Dependence and the Permanence Illusion

In fact, this excessive dependence on digital devices to hold our memories might have some negative consequences. Licklider's human-machine symbiosis interaction may have gone so far that we experience anxiety when we lose connection: a dead battery or a service drop can make us feel handicapped. Also, we rely on remembering the location where we found or recorded the information, expecting that once we intend to recover it, it will be there, intact.

Privacy and Ownership

Also, offloading content that we rely on for our memories to a third-party brings up many questions related to privacy. Who owns the content that we trust will help us revisit our past moments? Will the platform that is hosting our personal content ever become obsolete? Will it ever be hacked? How does the way the content is delivered to us contribute to reshaping our memory?

Concerns Turn Into Opportunities

Having information at our fingertips is reshaping our brain. One of the key motivations behind this thesis is raising awareness of some of the implications of offloading our memories to mobile devices and showing some of the opportunities that are now available. So, the question is: how can we develop technologies to support human memory that augment our brain's internal mechanisms for memory?

Steps Towards a Memory Augmentation Interface

A Symbiotic Interface Manifesto

Inspired by Licklider's vision on human-machine symbiosis [27], Engelbart's ideas on computer-based augmentation [28] and Pattie Maes's recent work at the MIT Media Lab [29], I will describe the symbiotic interface paradigm, an emerging trend in human-computer interaction that is the conceptual grounding of this thesis.

A symbiotic interface is the unified fusion between the person and the machine. It functions an extension of our minds and bodies and can assist us in overcoming our limitations and realizing our goals. Some applications include intelligence augmentation, memory augmentation, motor augmentation, sensory augmentation, sensory substitution, augmented decision making, subconscious and subliminal interfaces, hybrid human-machine creativity and more (Maes, 2016). Next, I will describe six key features; symbiotic interfaces are:

[27] Licklider, J. C. R. (1960). Man-Computer Symbiosis. *IRE Transactions on Human Factors in Electronics*, HFE-1(1):4–11

[28] Engelbart, D. C. (2001). Augmenting human intellect: a conceptual framework (1962). *Packer, Randall et Al. Ken. Multimedia. From Wagner to Virtual Reality. New York: WW Norton & Company*, pages 64–90

[29] Maes, P. (1994). Agents that reduce work and information overload. *Communications of the ACM*, 37(7):30–40

1. Digital

Symbiotic interfaces rely on digital computation to perform. Computers are now mobile and ubiquitous -from wearables to biosensors to head mounted displays- and its widespread use has turned us into cyborgs.

2. Integrated

Symbiotic interfaces enable an intimate integration between the human and the machine, tightly coupling the two. The goal of a symbiotic interface is to reach a human-machine symbiosis.

3. Empowering

Symbiotic interfaces increase human potential. They bring together the user and technology, making people more aware, more mindful and more empathetic. They can restore decaying functions of your body and mind. After using a symbiotic interface, we discover something new about ourselves that we couldn't do before.

4. Proactive

Symbiotic interfaces take initiative. They actively engage instead of waiting for the user to initiate interaction.

5. Disappearing

Symbiotic interfaces eventually fade and become part of us, like the cane becomes part of the blind man, revealing in the process something new about the human condition.

6. Perceptual

Symbiotic interfaces filter our perception, enhancing and mediating human perception, altering how we perceive the world by adding, subtracting or modifying stimuli before they are passed onto our perceptual system.

A Symbiotic Interface for Memory Augmentation

For this thesis, I will focus on human memory augmentation. More specifically, I will concentrate on the process and implementation of a symbiotic interface for long-term memory augmentation; showing how in the process we can use interfaces to get new insights on human intelligence.

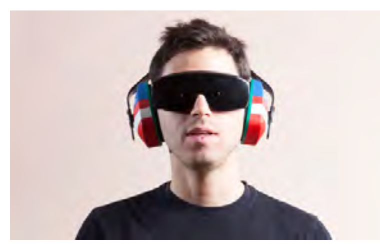

Figure 10: Joshua Foer, 2006 USA memory champion. Credit: Christopher Lane

The Memory Palace Method

In order design an interface for augmenting memory, the first step I took was learning how the experts do it. In competitive memory championships, memory athletes can perform surprising feats, such as memorizing 3,000 decimal digits in under one hour. After learning about this, Joshua Foer, a freelance journalist decided to do a story on memory competitions. Then, after finding out about the methods memory athletes use, he decided to try it out himself; after just two years of training, Foer won the 2006 US memory championship. Foer is not a savant or claims to have a particularly good memory before starting to train, he simply used the method all memory athletes use: The Memory Palace [30].

[30] Foer, J. (2012). *Moonwalking with Einstein: The Art and Science of Remembering Everything*. Penguin Books, New York, reprint edition edition

The memory palace is not a new method: it was widely used in ancient Greece and Rome as early as 60 B.C. before writing was widespread and was used mainly to facilitate public speaking. The method served as an effective mnemonic device when oral culture was the primary channel for transmitting knowledge. The memory palace can be used to memorize (almost) anything; lists of words, sequences of digits, languages, presentations and more. And the best part is you don't need any special abilities to use it: With practice, anyone can learn it.

Figure 11: The memory palace was often used in ancient Greece as a mnemonic device to support public speaking. Credit: Cicero Denounces Catiline, fresco by Cesare Maccari, 1882-1888.

Origins of the Memory Palace

Cicero in "de Oratore"[31] recalls the story of how Simonides of Ceos invented the memory palace method: Simonides was attending a banquet at a wealthy nobleman's house when a message was brought for him to go outside. Simonides went out, but when he came back in, the roof had collapsed, killing the host and all his other guests. After the accident, the friends of the victims wanted to bury their deceased friends but were unable to tell them apart, as they had been completely crushed.

[31] Cicero, M. T. (2001). *Cicero: On the Ideal Orator*. Oxford University Press, New York, writing in book edition edition

The story goes that Simonides was able to identify them by thinking of the locations of the table in which they were sitting. Leading to conclude that "the best aid to clearness of memory consists in orderly arrangement." [32]

[32] Yates, F. A. (1999). *The art of memory*. Number v. 3 in Selected works / Frances Yates. Routledge, London ; New York

How to Use the Memory Palace

In the original memory palace, what you do is you imagine a scene, say a room, with as much detail as you can. Then you find a graphical mental image that will help you remember the content you want to memorize. Next, you place that image in the scene. When you want to recall the content, you think of the space, not the content, and the image will naturally emerge [33].

[33] Yates, F. A. (1999). *The art of memory*. Number v. 3 in Selected works / Frances Yates. Routledge, London ; New York

I will use an example to illustrate the method. Let's suppose you wanted to use the memory palace method to help you remember that the Green Bay Packers were the first team to win the Super Bowl in 1967. To do this, first, imagine a room of a house as vividly as possible; you will use this image as your scene. Then, think of an image that reminds you of the Green Bay Packers. This image could be, for example, a courier holding a stack of packages, because of the similarity between the Packers and the packages. Next, place the courier holding the packages in the room you imagined. Then, try to visualize the combined scene. Finally, when recalling the content, think of the room or scene we imagined in the first step, not the content. By thinking of that room you will be able to easily recall what you intended to memorize.

This method is especially effective for memorizing sequences of items. In such cases, the method involves imagining a route in a mental architectural space and placing mental symbols along that route. When recalling the sequence, simply revisit that route mentally to recall the images that will trigger the concepts you intended to memorize (Foer, 2012). So, when Joshua Foer is recalling the 3,000 digits he memorized, he is mentally following this process.

Drawbacks of the Memory Palace

In the memory palace, everything happens in your head. The method relies heavily on imagination, and this can be complicated for people that are getting started. I will try to conceptually break down the methods into cognitive tasks. First, imagining a space vividly can be challenging for novices. Even for architects, it takes years of training before they start to visualize their designs clearly in their minds. Second, visualizing a symbol can also be complicated for people who are not used to working with images. Third, combining the two images effectively requires extensive training. The intent is to overcome these problems by building and testing an interface to help users construct experiential memory palaces for remembering sequences of items. In the next section, I will describe how I plan to address these issues.

An Intuition: Memory, Space and Navigation

Architects know how hard it is to design just by using their imagination. And in contrast, how three-dimensional (3d) modeling or drawing can significantly ease the cognitive load and facilitate the visualization of spaces that don't yet exist. Drawing does for architects what writing does for journalists: it allows them to discharge their internal memory, freeing up space to reflect upon their own work.

After learning about the memory palace method, I started thinking about how to build a visual version of the palace. If we know that imagining spaces is complicated and in contrast, visualizing them makes things easier, would a virtual three-dimensional palace help new users get started with the method?

One of the first concepts and prototypes was a three-dimensional version of the palace. I modeled a digital version of a virtual space and placed 3d objects along a route that would serve as cues for memory. Each room was spatially unique, in an attempt to make them more memorable, and the space flowed in sequence to facilitate the orientation of the user.

However, navigating virtual environments is no easy task. Anyone that has played 3d video games knows that navigating a virtual space -even in virtual reality- can be disorienting; in contrast, navigating

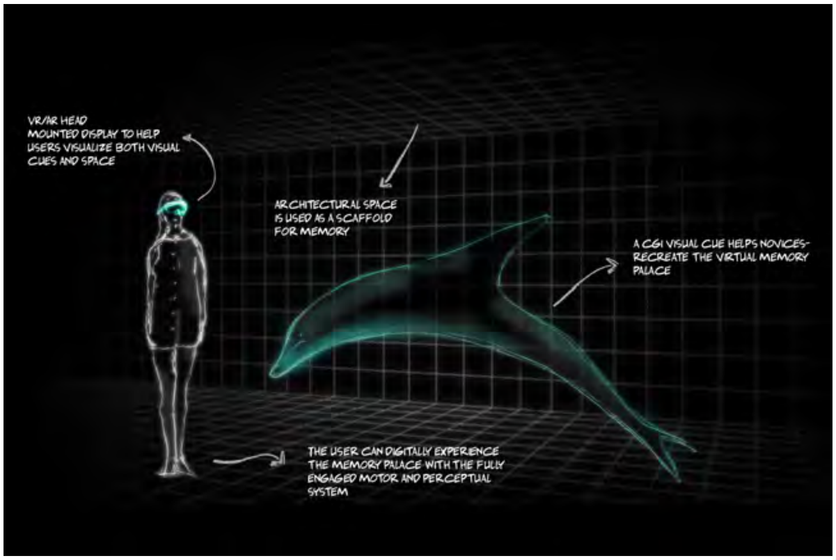

Figure 12: Early sketches for a virual memory palace.

the world is a task we do effortlessly. So, can we use real architecture as a support for memory instead of building a virtual memory palace?

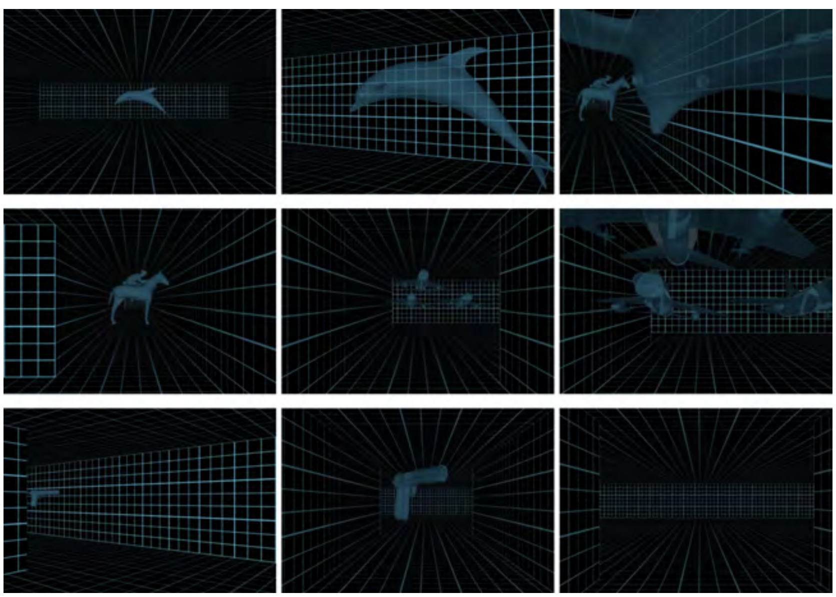

Figure 13: The first step towards building a visual memory palace was making a fully virtual version.

Thesis Statement: Memory, Space and Navigation

This leads me to the general hypothesis. In this thesis, I will try to show how we can take advantage of the connection of spatial learning and memory to facilitate memorization.

Humans are surprisingly good at navigating space. People commute everyday from home, to their work, and sometimes even take an unexpected detour for coffee -most of the time- without getting lost. Everyday we navigate through labyrinthic architectures effortlessly, and this is not a trivial cognitive task. There is lots of information that is being processed without us even being aware. So, perhaps if we imagine the space in our heads, then by physically experiencing a sequence of familiar spaces might lead to better memory.

Episodic Memory and the Role of the Hippocampus

Before we address the next steps on how to design an interface for human memory augmentation, first, I will clarify what type of memory I will be addressing.

Human memory is not a single entity, and it doesn't occur in the vacuum - memory is a complex set of processes that we are just beginning to understand. In the scientific literature, human memory is divided between short-term and long-term. While short-term memory remains for only about 18 to 30 seconds, long-term memory can persist indefinitely.

Long-term memory is commonly labeled as either implicit memory or explicit memory. Implicit memory helps people perform tasks without conscious awareness of these previous experiences; it is acquired and used unconsciously and can affect thoughts and behaviors. In contrast, explicit memory is conscious; we use it when we want to recollect factual information, previous experiences and concepts at will (Ullman, 2004).Intuitively, when we refer to memory we refer to explicit memory.

Explicit memory can be further subclassified into two categories: semantic memory, which stores factual information, and episodic memory, which stores specific personal experiences. (Tulving and Donaldson, 1972). For example, semantic memory might hold information about what surf is, and in contrast, episodic information might contain information about an amazing wave you rode this summer.

Episodic Memory

Semantic memory is the mechanism we use when recalling facts, ideas, meaning and concepts. In contrast, episodic memory is a type of long-term memory that relates to events and personal experience. It's the mechanism that allows us to answer autobiographical statements; that is, answer the questions to "where" and "when"? For example, when you think about what you ate yesterday for dinner, you are going to remember what you ate, but also where you ate it and when you ate it. Episodic memory is experiential, so there is always a spatial and temporal component associated with that memory. Some theories also hold that episodic memory is the key to help us imagine and think about the future[34]For this thesis, I will focus on memory augmentation using episodic memory.

[34] Hassabis, D., Kumaran, D., and Maguire, E. A. (2007). Using Imagination to Understand the Neural Basis of Episodic Memory. *Journal of Neuroscience*, 27(52):14365–14374; and Hassabis, D., Kumaran, D., and Maguire, E. A. (2007). Using Imagination to Understand the Neural Basis of Episodic Memory. *Journal of Neuroscience*, 27(52):14365–14374

The Hippocampus

Current neurological research has demonstrated that there is one part of the brain we know is critical for episodic memory: the hippocampus (Gluck et al., 2014). The hippocampus is a horn-shaped structure in the medial temporal lobe of the human brain. Research on patients without a hippocampus shows that subjects are unable to form new autobiographic (episodic) memories, while still keeping other functions of memory intact. They don't experience drops in IQ or lose the ability to learn new motor skills, but instead, their day restarts every few seconds.

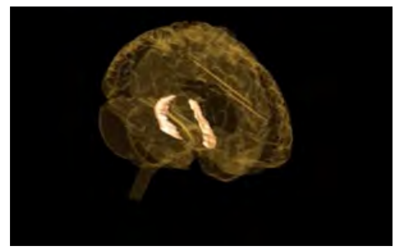

Figure 14: The hippocamus is a horn-shaped structure in the medial temporal lobe. It is responsible for long-term memory formation.

The role of the hippocampus in episodic memory formation has been studied extensively in fMRI experiments, but to date, no mechanism has been identified to explain how neural ensembles enable encoding and retrieval of memory episodes. However, there are some parallels between the work of memory in rats, a mammal that shares a close resemblance in the structure of the brain, which might help us better understand episodic memory formation in humans.

Place Cells in the Hippocampus

The hippocampus in rats is critical for both episodic memory formation and spatial navigation in rats. John O'Keefe won the Nobel Prize in physiology and medicine in 2014, for his experiments on episodic memory in rats, revealing the role of place cells for the first time, a type of neuron found in the hippocampus. Place-cells show an increase in firing rate and firing pattern when the animal moves through a specific part of a maze [35].

[35] O'Keefe, J. and Nadel, L. (1978). *The hippocampus as a cognitive map*. Clarendon Press ; Oxford University Press, Oxford : New York

The hippocampus plays a key part in both memory and representation of space in rats. More specifically, it is involved in the formation of episodic memory as well as spatial memory used in navigation [36]. On the one hand, in episodic memory, the rat's hippocampus is responsible for the linkage of events; on the other hand, in spatial navigation, the hippocampus is responsible for linkage of spatial locations.

[36] O'Keefe, J. and Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. *Brain research*, 34(1):171–175

These experiments have been recreated by Matt Wilson at The Picower Institute for Learning and Memory at MIT together with other major contributions on the role of the hippocampus in episodic memory formation [37] - confirming the unifying property of both navigation and episodic memory and the importance of the hippocampus in both activities in rats.

In Wilson's experiments, a hole is drilled in the rat's skull, inserting a microelectrode array probing into the hippocampus. Then, the action potentials in the neurons are detected using the electrode while the rat is moving freely through a track [38].

[37] Foster, D. J. and Wilson, M. A. (2006). Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature*, 440(7084):680–683

[38] Ji, D. and Wilson, M. A. (2007). Coordinated memory replay in the visual cortex and hippocampus during sleep. *Nature Neuroscience*, 10(1):100–107

The Role of the Hippocampus in Humans

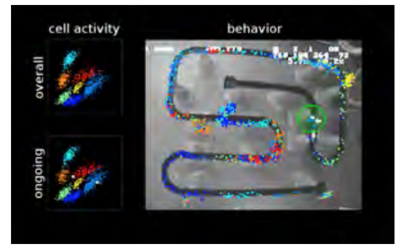

Figure 15: Matt Wilson shows how unique neural patterns fire at each specific location in rats. Credit: Wilson Lab

In humans, current brain imaging techniques have one critical limitation: there are currently no methods that allow for hippocampal activity recording while humans move through space. Also, for technical and ethical reasons, it is not possible to insert an electrode through the human skull while subjects move freely in space. Yet, there seems to be a close relationship between the research on memory in rats and what humans can do.

Scientists have speculated that the spatial component of episodic memories may be encoded by place cell activity in humans. Limitations in current brain imaging techniques, do not allow monitoring of hippocampal neural activity while moving through space; but recently, fMRI studies have shown in-place spatial navigation simulation, that is, thinking about a route without actually moving, and long-term memory both engage in hippocampal activity.

The Hippocampus of Memory Champions

The role the hippocampus plays when memory athletes memorize has also been a topic of recent study. Brain scans of superior memorizers, including memory athletes, have shown that using the memory palace method involves activation of regions of the brain involved in spatial awareness, such as the medial parietal cortex, retrosplenial cortex, and the right posterior hippocampus [39].

[39] Maguire, E. A., Valentine, E. R., Wilding, J. M., and Kapur, N. (2002). Routes to remembering: the brains behind superior memory. *Nature Neuroscience*, 6(1):90–95

When memory athletes memorize, they are using the memory palace method to unconsciously take advantage of spatial memory to facilitate encoding, storing and retrieval of information. I take this method as an inspiration of how to design for memory augmentation and suggest that we can use interfaces to direct the way people memorize, so the parts of the brain that are active in memory athletes are stimulated for novices.

So, if current research on brain scans of superior memorizers when using the memory palace, and also like rats, show hippocampal and activation of areas that belong to spatial navigation:

Research Question

Can we passively stimulate hippocampal engagement during memorization tasks to increase memory recall?

Preliminary Behavioural Tests on Memory

Next, I will describe four behavioral tests that preceded and contributed to insights to the current version of the memorization interface. These are not full experiments, but rather intuitions that contributed to a key insight that has been incorporated in the current version of the memorization interface. The purpose was not gathering accurate experimental data, but rather quick iterations to understand which behaviors I could take advantage of.

All these tests aim towards engaging the neurological processes memory athletes use, and use the symbiotic interface paradigm as a tool to facilitate those mental processes for novices. Not all tests are described here, but a selection of the four insights that were later used for the final version of the interface.

Insight 1: Architecture Can be Used as a Support for Memory

If our minds are constantly encoding the locations we have traveled, and these are linked to memory, would an image of the location, combined with a visual cue facilitate the memorization process? I tested this idea on 30 college students, none of which were previously trained in the memory palace method. The goal was to try to memorize the ten first champions of the Super Bowl in chronological order.

Next, I showed pictures of places that corresponded with each of the locations and combined them with an image that reminded subjects of the content they wanted to remember. For example, to help participants remember that the Dallas Cowboys won the Super Bowl, I superimposed an image of the location with a visual cue of a man riding a horse.

Figure 16: Images of places we know can be used as an effective support for memory.

I showed subjects a set of 10 images, once, for 3 seconds each. During the test, the images were projected on a screen in a physically accurate order, so the sequence of images corresponded to the marked points on the route, in the same order.

In these tests, instead of relying exclusively on imagination, I engaged the subject's visual system. Without previous knowledge of the memory palace, about 90% of the participants were able to effortlessly remember the list of the ten first Super Bowl champions two minutes after the task. Instead of using imagination for scene generation and object placement, as in the original memory palace method, if we use visual material and superpose images of a space, I observed that memorization is facilitated.

The key contribution of the first test was suggesting that the memory palace method is easy to learn with visual content of architectural images the subject is familiar with.

Insight 2: Visual Memory Palace Locations can be Reused

Can we reuse the architectural locations that we use for the visual memory palace with different content? I tested this idea on a subset of the subjects from the previous experiment. The goal was to help them memorize ten digits of π, after 3.1415. The cutoff was set after 5, which was the digit participants were not familiar with.

Figure 17: Memory locations in the memory palace method can be reused multiple times with different content.

This time, the locations showed were exactly the same, but now the participants saw a color-coded digit instead of an image. The numbers were displayed in three dimensions and were anchored to the architectural scene. For example, a cyan colored number five was resting on the entrance staircase of the Media Lab.

The colors used for the numbers was consistent; each number was assigned to only one color, and if the number appeared again, the same color was used.

Encoding symbolic visual information, numbers, proved to be more challenging to retain. For this reason, the image exposure time was increased to 6 seconds and the sequence of images was displayed three times. but subjects were able to make distinctions between the two study sequences.

The key contribution of the second test was suggesting that the locations of the visual memory palace can be reused multiple times for different content. An indirect contribution is that encoding symbolic information can be also used successfully.

Insight 3: The Visual Memory Palace Activates Episodic Memory

How long do the memories encoded with the memory palace last? After talking to subjects the next week, they were still able to recall the memorized content with a high recall rate. This finding was accidental, as I wasn't expecting for memories so be so durable, but contributed to a valuable finding.

The key insight was realizing that the content memorized with the visual interpretation of the memory palace is effortlessly stored in long-term memory.

Insight 4: Augmented Reality Makes a Mobile Memory Palace

Can we use real architecture as the scenes of the memory palace and overlay the visual cues in augmented reality? I tested this idea on a reduced set of participants to see if information could be encoded on-site.

For this test, I used the same visual cues from test one, the Super Bowl champions. But instead, I displayed in augmented reality the visual cues over a real architectural location. The participants walked along a route and at each location saw the visual cue. Participants were tested for memory recall on the next day. The recall rate of this test was close to 90%, similar to the first test. Some insights from using augmented reality include:

First, realizing that real architectural locations work instead of images. This means that taking a picture of the location in advance is presumably no longer required. By building on the spatial qualities of augmented reality, it's possible to take advantage of the information we encode in spatial navigation.

Second, cues are independent of the background or location. I used the same set of images (Super Bowl champions) as cues in augmented reality, but on a different route. The recall didn't seem to have an effect on which background was used.

Third, the palace can be mobile. When designing an interface, each user could use their own location. There is no need to build a scene in 3d or collect pictures of places the user has been in advance. Instead, the cues can be played on-the-fly. This also means that because the cues and scenes are independent, the cued content could be potentially shared between users.

Fourth, movement and experience seem to add another layer of memorability to the locations.

NeverMind

For this project, I took a non-invasive approach. I was interested in testing if some of the behaviours we observe when rats navigate through space can be transferred to humans.

Some of the questions I was aiming to answer were:

- Can I facilitate memorization by having people move through space to engage their hippocampus?
- Can people use vision, spatial navigation, and architecture instead of just imagination for memorization?
- Can I take advantage of the fact that our brain is subconsciously building a map of our environment and use that as a support for memory?

What NeverMind Is

NeverMind is an augmented reality interface designed to help people memorize effectively. As a starting point, I take the memory palace method, an ancient technique for memorization. The method is still used today by memory champions, however, I modify and develop it to make it accessible to anyone.

I use the symbiotic interface paradigm to activate the mental processes memory champions use, stimulating the processes that lead to episodic memory encoding in users. NeverMind has two parts, an iPhone app that handles the user interaction, and an augmented reality head-mounted display that shows the content that the app sends.

NeverMind shares many aspects of the original memory palace method. However, there are three key differences that make this method unique.

First, instead of using imaginary spaces and routes, NeverMind uses real architecture and spatial navigation, engaging the hippocampal activation of the brain. While memorizing with the interface, the

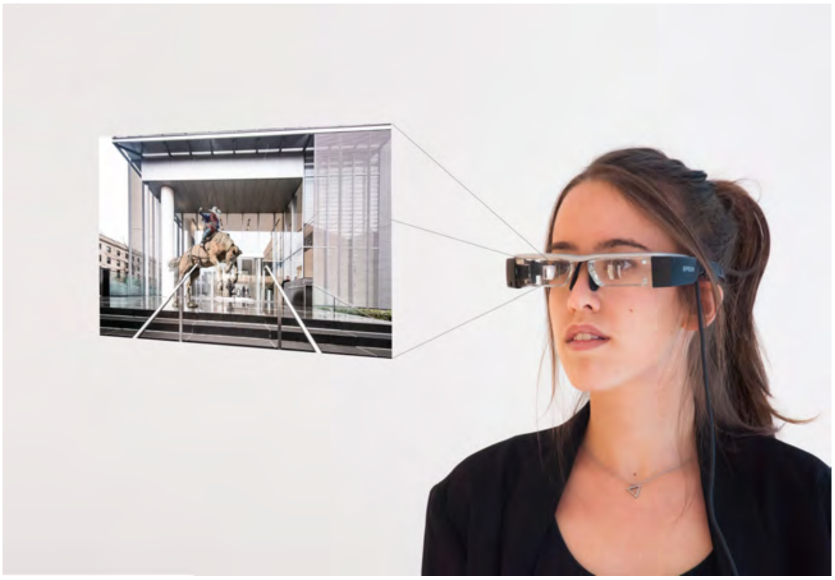

Figure 18: NeverMind is an augmented reality interface designed to help people memorize effectively. The NeverMind app handles user interaction and the headset displays the information so the user sees the content at her current location.

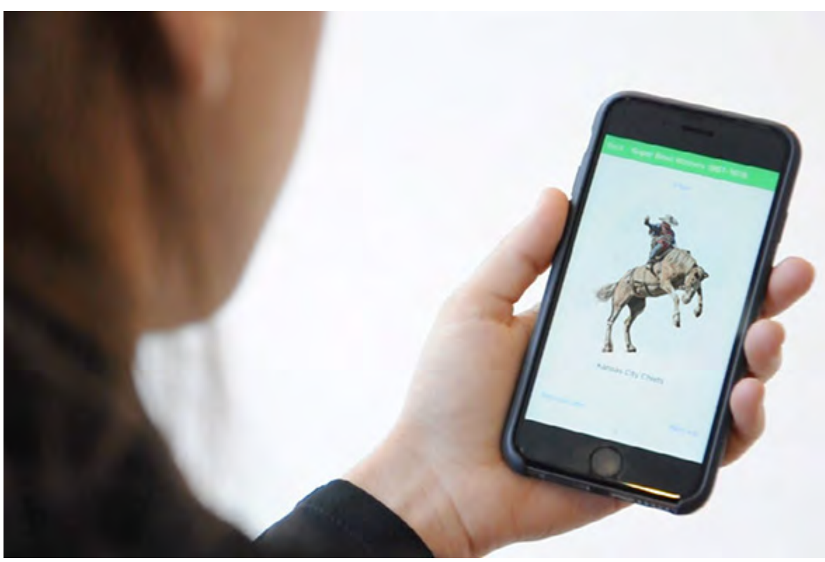

Figure 19: An iPhone app handles user interaction and and AR display shows visual cues to the user.

user participates in movement and walks along a route that will help her unconsciously build a semantic map for their memories.

Second, instead of imagining a graphic representation of the content she wants to memorize, she sees the content to memorize in augmented reality, engaging the brain in a visual task. These two changes unconsciously direct the user to store memorized content in long-term memory and enable her to memorize in one-shot.

Third, instead of combining an imaginary space with an imaginary cue, NeverMind combines the two images on the spot. The interface handles the fusing and embedding of a space and the cue into a single experience.

Inspired by methods used by memory champions, NeverMind facilitates memory encoding by engaging in hippocampal activation and promoting task-specific neural firing. NeverMind pairs spatial navigation with visual cues to make memorization tasks effective and enjoyable. This is done by using an interface that stimulates the hippocampus and other mental processes involved in navigation.

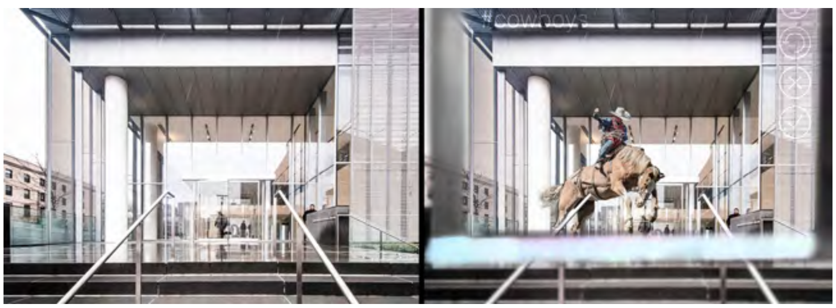

Figure 20: (left) Picture of the location without the interface. (right) Using NeverMind, the user walks to an architectural scene and sees a visual cue in augmented reality.

NeverMind is essentially an experiential version of the memory palace. However, instead of using imagination, the interface uses pictures in augmented reality. And instead of imagining a space, the interface uses architecture and movement. By pairing the memorization task with a spatial navigation task, I'm directing the user's perception to engage in episodic memory, instead of using semantic memory.

In short, NeverMind is a tool to facilitate memorization through a single exposure by guiding the user's perceptual system into using episodic memory. People tend to use semantic memory when memorizing and encoding through repetition; however, by using interfaces, the way our brain encodes information can be manipulated to remember long term content with a single exposure.

Additionally, NeverMind doubles as an open-source platform for researchers to conduct high-level experiments on episodic memory, spatial navigation, and architectural space.

Figure 21: The visual cues are embedded in architectural space to help users memorize.

How to Use NeverMind

Memory Encoding

To memorize with NeverMind, the user takes a walk through a building they are familiar with. With this method, the architectural spaces are the equivalent to the imaginary rooms of the original memory palace. At each room, the user queries the app to display an image. This allows for a specific image to be mentally bound to an architectural location, that way during recall, each location will trigger a specific memory.

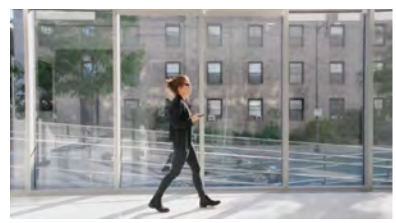

Figure 22: To memorize with NeverMind people go on a walk through an architectural space.

Then, in order to memorize a sequence of items, the user physically walks to the next room and queries the interface for the next image to be displayed. Because augmented reality allows for the user to be aware of the spaces they are in, association and embedding of an image to a specific location becomes experiential instead of imaginary.

With NeverMind, the user only needs to see images once in order to memorize effectively. Experiments show that three seconds of exposure is enough for content to remain in memory. Because the user is only seeing the images once, I will refer to this process as one-shot memorization, inspired by Josh Tenenbaum's concept of one-shot learning [40].

[40] Tenenbaum, J. B., Lake, B. M., Salakhutdinov, R., and Gross, J. (2011). One shot learning of simple visual concepts. In *Proceedings of the 33rd Annual Conference of the Cognitive Science Society*, volume 172, page 2

Memory Retrevial

To recall the content, the user simply needs to think of the route she took through the building. Like the original memory palace method, the route she used will help them retrieve the content they intended to memorize. However, because our brain is collecting spatial information unconsciously while we move through space, this process becomes easy.

In NeverMind, augmented reality allows for the user to be aware of the spaces they are in, meaning that association and embedding of an image to a space becomes experiential instead of imaginary.

NeverMind Interface Details

The current implementation of the NeverMind interface is divided into two parts: (i) an iPhone app that handles user interaction and (ii) an Epson Moverio BT-200 augmented reality headset that displays the graphical content the app sends.

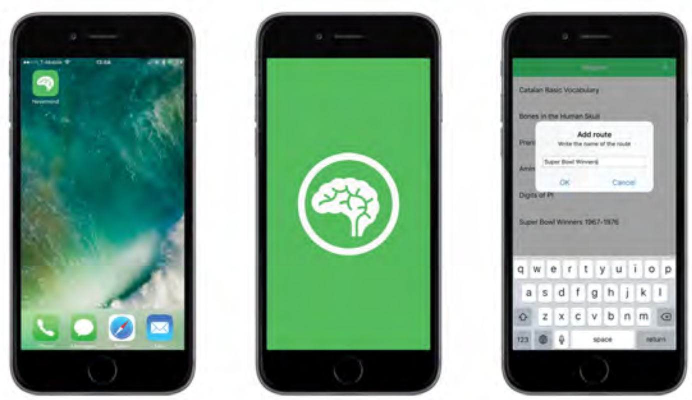

Figure 23: (left) NeverMind app on home screen (middle) Splash screen (right) Pop up menu to add a new playlist.

NeverMind iPhone App

The iPhone iOS app is developed using Objective-C and Xcode 7 and it built for iOS 10.3. After launching the NeverMind app, users have the option to either set up a new "knowledge playlist" or play an existing one. "Knowledge playlists" are lists of items with images associated with them.

The app isn't preloaded with content, but users can easily create a new playlist by tapping on the plus sign. A menu will pop up, prompting the user to name the new playlist. Next, the newly created playlist will appear on the main menu. Then, the user can tap to add content to each playlist. By default, the user will see ten empty slots, but new slots can be added or deleted.

Each slot has two empty fields; one for text and one for images. After tapping on the text field, the user can type the name of the first

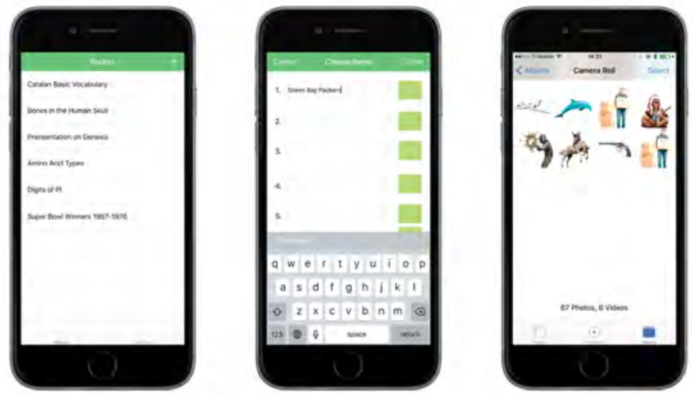

Figure 24: (left) Custom user playlists (middle) Slots for adding content to a new playlist (right) Users can add new images from the camera or browser.

item in the list he wants to memorize. Then, he can add the image by tapping on the green box from the right.

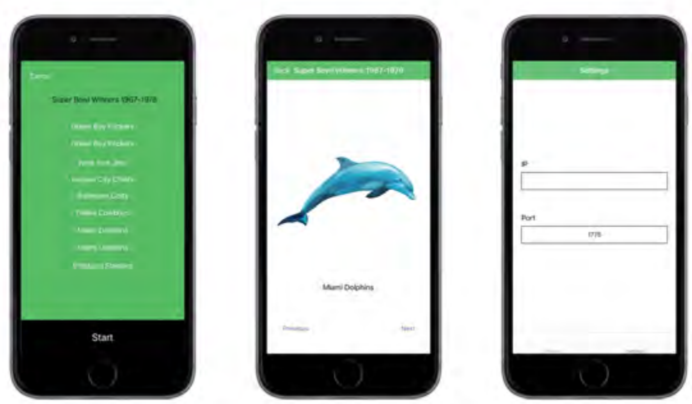

Figure 25: (left) In train mode, users (middle) The app also displays what the user is seeing in augmented reality (right) Set up screen for communication between the iPhone app and the headset app.

After tapping on the image field, the user will be able to select an image from the camera or the browser. The images are the graphical content that will help users cue their memories during encoding and retrieval tasks. After finding the right one, the slot will be full. The same process can be repeated to fill up all slots with items that the user intends to memorize. Next, the playlist will be saved automatically.

NeverMind Moverio App

The Epson Moverio BT-200 augmented reality headset comes with a mobile receiver that runs on Android. To display the images that the iPhone app sends, there is a simple Unity3d scene built for Android that displays a picture frame with the received content.

The communication between the iOS app and the Unity3d app is made with sockets. In the current version of the app, the user needs to enter the IP address that is displayed in the AR app. This app was developed together with Marc Exposito.

NeverMind Applications

NeverMind is conceived with two main uses in mind: (i) a tool to help memorization, (ii) a research tool for studying episodic memory.

A Tool to Help People Memorize

Part of my motivation for this thesis is to change the way students memorize. Students spend a lot of time memorizing based on repetition. This thesis suggests that there are more effective study methods that are in line with the way our brain stores information.

With NeverMind, I provide a framework for learning how to memorize effectively. I see potential uses in education, as a method to bootstrap knowledge as a starting point before making associations and inferences that are characteristic of higher levels of understanding.

The system could be used, for example, for medical school students to facilitate learning the branches of the trigeminal nerve, the details of the lymphatic system and many others. Other uses of the interface include public speaking preparation and training.

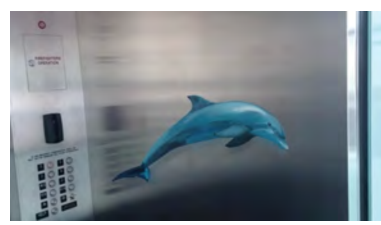

Figure 26: The user simply needs to think of the space they were in to easily retreive the memorized content.

A Research Tool to Study Episodic Memory

After developing NeverMind, there are many experiment ideas that emerged to test how spatial navigation and architectural space can contribute to our memory. Instead of testing out all possible experimental variations, I'm making NeverMind available to the public.

All the code is available for download on GitHub, open source, so users can either build the existing version or build on top of the existing code to add further functionality to meet their needs.

I expect the tool to offer a non-invasive, cheap platform for behavioral insights on human episodic memory and its relationship to movement and architecture. Because of current limitations in technology, using augmented reality opens up many opportunities for new behavioral, cognitive experiments.

What NeverMind Isn't

The goal of NeverMind is not to replace other methods of learning in educational contexts. My intent is not to design a knowledge transfer tool that implants words without meaning. Education should be about discovery, experimentation, and curiosity. And while memorization is useful and essential for learning, it shouldn't replace other forms of meaningful understanding.

Your Hippocampus Can Grow

With the advent of mobile phones, we now reach inside our pocket and information is instantly available at our fingertips. Today, there is no need to remember our relative's phone numbers or the exact location of a bar that serves excellent bubble tea, because we can just take out our phone and look it up.

The way we navigate space has also changed. We now often rely the GPS on our phone to take us to a restaurant we have at least gone five times and don't go through the mental burden of trying to plan the shortest path. Instead, we tap an address and follow the directions on our GPS.

We no longer remember specific content, but instead, we just remember where to find it; and this is having physiological effects on our brain[41].

[41] Sparrow, B., Liu, J., and Wegner, D. M. (2011). Google Effects on Memory: Cognitive Consequences of Having Information at Our Fingertips. *Science*, 333(6043):776–778

Why Memorization Matters

Even if you are not interested in remembering information that you could just find on your phone or write on a piece of paper, like for example, who won the Super Bowl in 1967; you might be interested in learning that by using memory and spatial navigation, we generate new neurons in the hippocampus. This means, our hippocampus can grow. It's not only about the content you memorize, but an opportunity to modify your brain, it's a form of exercise.

People with a smaller hippocampus stand at greater risk of memory loss, post-traumatic stress disorder [42], depression [43], dementia, and schizophrenia. Because we rely so much on mobile these devices, their drawback and consequences are something we need to consider when designing the future's interfaces.

[42] Gilbertson, M. W., Shenton, M. E., Ciszewski, A., Kasai, K., Lasko, N. B., Orr, S. P., and Pitman, R. K. (2002). Smaller hippocampal volume predicts pathologic vulnerability to psychological trauma. *Nature neuroscience*, 5(11):1242–1247

[43] Chen, M. C., Hamilton, J. P., and Gotlib, I. H. (2010). Decreased hippocampus volume in healthy girls at risk for depression. *Archives of general psychiatry*, 67(3):270–276

Hippocampal Health and Training

There is an emerging area of research of hippocampal health that is now starting to take off. Veronique Bohbot has developed a "Spatial Memory Improvement Program" that focuses on stimulating the hippocampus to reverse volume loss.

Studies show that mnemonic training reshapes your brain to resemble the ones of memory champions [44]. Other studies have shown, that actively engaging in spatial memory, in tasks such as way finding, thickens your hippocampus [45].

[44] Dresler, M., Shirer, W. R., Konrad, B. N., MÃijller, N. C. J., Wagner, I. C., FernÃąndez, G., Czisch, M., and Greicius, M. D. (2017). Mnemonic Training Reshapes Brain Networks to Support Superior Memory. *Neuron*, 93(5):1227–1235.e6

[45] Iaria, G., Petrides, M., Dagher, A., Pike, B., and Bohbot, V. D. (2003). Cognitive strategies dependent on the hippocampus and caudate nucleus in human navigation: variability and change with practice. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 23(13):5945–5952; and Maguire, E. A., Valentine, E. R., Wilding, J. M., and Kapur, N. (2002). Routes to remembering: the brains behind superior memory. *Nature Neuroscience*, 6(1):90–95

What's New in NeverMind

Previous work on memory augmentation relied on offloading storage and retrieval of memory to external hardware devices. Also, the design from the conceptual, hardware and software perspectives is different from the one I have described here.

For NeverMind, I have followed a different approach: In place of using technology as an external memory prosthetic, I use the interface as a filter to direct long-term memory. The intent is to build and test an interface to help users construct efficient strategies for remembering sequences of items.

There have been other attempts at recreating a digital memory palace [46], however, this to my knowledge, this research is unique in using architecture as the memory palace scene, movement and spatial navigation to transition between scenes and augmented reality to display visual cues.

[46] Fassbender, E. and Heiden, W. (2006). The virtual memory palace. *Journal of Computational Information Systems*, 2(1):457–464

Other previous work focused on studying the influence of space through static scenes, video or virtual reality in a virtual memory palace(Legge et al., 2012).

However, the advantage of using augmented reality is that your navigation system is not being impaired and your visual and spatial perception mechansisms, such as the vestibular system are fully engaged. Unlike in virtual reality, there is full immersion and your sensory apparatus is fully engaged.

Also, by using augmented reality each user can use their own locations without having to virtually recreate the scene content in 3d. Your can turn your own house or your route from home to work into a memory palace.

NeverMind: Experiments

Experimental Methods

I have tested NeverMind experimentally with 14 subjects. Participants were all college student volunteers from different educational backgrounds: 55% of the participants claimed to have college level training in a visual discipline (design, architecture or visual arts) and the other 45% studied STEM disciplines. 55% of the participants were male, and 45% of the participants were female.

Before starting the experimental task, I asked participants to self-evaluate on their ability to memorize. 64% of the participants stated in the survey they had average or below average memory.

Each participant performed two memorization tasks. One, given a printed list of 10 items, memorize the list; two, use NeverMind to memorize another list of 10 items. The starting task was randomized.

I tested the subjects on two similar lists of items containing a list of Super Bowl champions in chronological order. I used a list of 10 Super Bowl champions from 1967 to 1976 for the NeverMind-based task and the champions from 1977 to 1986 for the paper-based task.

Super Bowl Champions 1967-2016
1967 Green Bay Packers
1968 Green Bay Packers
1969 New York Jets
1970 Kansas City Chiefs
1971 Baltimore Colts
1972 Dallas Cowboys
1973 Miami Dolphins
1974 Miami Dolphins
1975 Pittsburg Steelers
1976 Pittsburg Steelers

Table 1: List of Super Bowl champions experiment participants memorized with NeverMind.

I verified that the subjects had no previous knowledge of the content they were tested on before running the experiment. Also, none of the participants had used the memory palace method before or were told about it at the time of the experiment.

Figure 27: NeverMind visual cues for the 10 item sequence experiment.

For the paper-based task, subjects were handed a printed list of 10 items and were told to memorize the content. For the NeverMind-based task, I used a 200-meter predefined path through a building, the MIT Media Lab, which all participants were familiar with before the experiment. For verification purposes, I showed a map in advance with the specific route we would take during the memorization task to make sure.

Next, I preloaded the interface with images for consistency in experiment results across subjects. For example, I used a picture of a man on a horse to represent the Dallas Cowboys, a picture of an airplane to represent the Houston Jets and so on.

Then, the subjects walked on the specified route, visualizing in augmented reality the content NeverMind displayed at each location. In all cases, the visual cue was displayed in augmented reality for 3 seconds; then the participants walked to the next location. The same locations, route, and images were used across all participants.

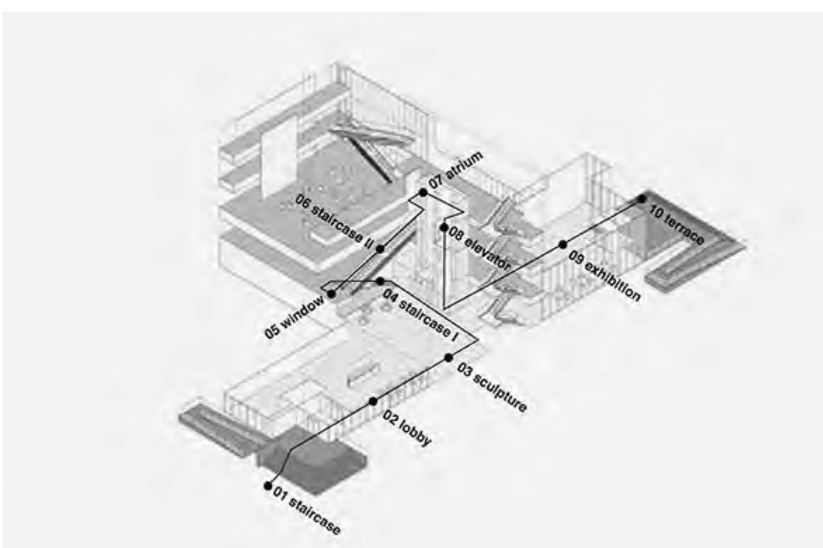

Figure 28: NeverMind users go on a route you are familiar with. The physical route the user takes will be used as the scenes of the memory palace.

Finally, I tested their ability to recall the content memorized. To do this, I sent out online surveys in three different time spans: after 2 minutes, after 24 hours and after seven days. The three surveys were identical. For both the augmented reality task, and the paper-based task, the survey had 10 slots to fill, allowing participants to select one of the 32 NFL teams using a drop-down menu. The form also had a "I don't remember" option for participants that were unsure of the result or didn't want to guess.

Experiment Results

Results show that the recall rate for 2 minutes after the experiment of both the NeverMind task and the paper-based task had similar values (NeverMind: Avg.=0.97, SD=0.06; Paper: Avg.=0.96; SD=0.07).

Task Type		3 min.	24 hrs.	3 days
NeverMind	Average	0.97	0.96	0.96
	Std.dev.	0.06	0.07	0.09
Paper Task	Avg.	0.96	0.43	0.35
	Std.dev.	0.07	0.33	0.26

Table 2: Recall accuracy for the experiment task using NeverMind compared to the paper based task.

After 24-hours, recall rate steeply dropped for the paper-based task but stayed steady for NeverMind (NeverMind: Avg.=0.96, SD=0.07; Paper: Avg.=0.43; SD=0.33),

7 days after the task the content recall rate with NeverMind held similar values to the 24-hour task, whereas the paper-based task continued to drop (NeverMind: Avg.=0.96, SD=0.09; Paper: Avg.=0.35; SD=0.26).

When questioned about the two methods, users claimed that studying with the NeverMind interface was either much more enjoyable (71%) or more enjoyable (29%) and effortless compared to the paper-based study method.

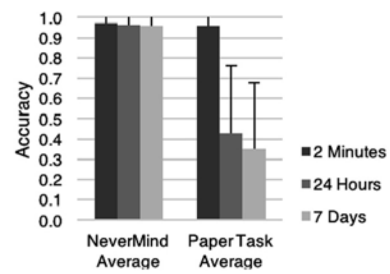

Figure 29: Recall accuracy for the experiment task using NeverMind compared to the paper based task.

Analysis of Results

I propose three takeaways from the experiment results: first; recall rate is tripled using NeverMind, second, one-shot memory is possible; third, interfaces can subliminally raise awareness.

Recall Rate is Tripled Using NeverMind

Content studied with NeverMind was remembered for longer than with a traditional study method, such as memorizing items from a printed list. Recall rate is tripled using NeverMind, suggesting that participants are using episodic memory to memorize the content.

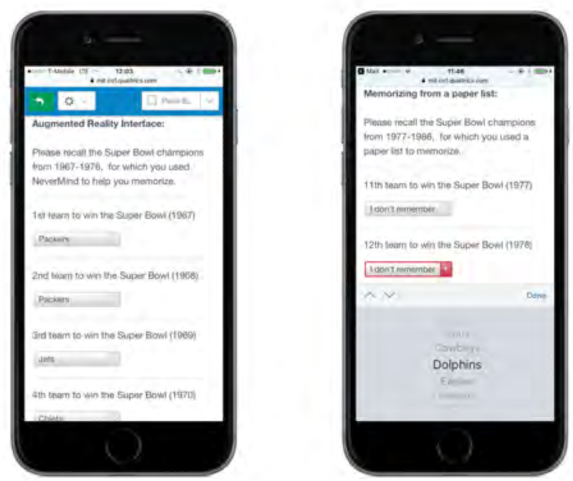

Figure 30: Participant received three online surveys, after 2 minutes, 24 hours and 7 days, to test their memory recall for content memorized with NeverMind and with a paper list.

Episodic memory refers to autobiographical experiences, and answers questions about *where* and *when*. In NeverMind, the *where* are the locations in the building, and the *when* refers to the sequence of items in space. Using episodic memory for tasks we tend to use semantic memory for is a counterintuitively effective strategy.

One-shot Memory is Possible

Participants only saw the content to memorize once, for 3 seconds, indicating that there are other effective memorization techniques that are not based on repetition that is more enjoyable and effective. The recall accuracy using NeverMind seems to be independent regardless the participant's gender, educational background or personal self-evaluation on their facility to memorize. One of the key takeaways from this experiment is that forming long-term memories with a single exposure is possible.

Interfaces Can Subliminally Raise Awareness

After the third recall task, many participants expressed surprise when realizing how easy it was to retrieve the content memorized with NeverMind compared to the paper based task. Some even expressed anxiety at the thought of trying to retrieve the content written in the paper list and not being able to remember what was there.

After the experiment, I asked participants to describe what they thought they were doing during each of the memorization tasks. In the paper-based tasks, most participants claimed that they were "repeating the names of the teams in their head" many times to try to remember the different teams. For the NeverMind task, most participants stated that they weren't particularly engaged or motivated in trying to remember what they were seeing.

During the recall tasks, some claimed that what they were doing is mentally simulating the route they took through the building, retelling the story of how they moved through space. Sentences such as: "In the lobby, I saw a cowboy, then I waked to the elevator and saw a dolphin," were often articulated when talking to the participants after the experiment ended.

This suggests that without being trained on the memory palace method, participants were able to memorize effectively. The interface stimulates some of the parts of the brain memory champions use when using the memory palace method. In sum, when using NeverMind participants discovered there is something that they can do that they didn't know they could do before.

Future Experiments: NeverMind is Free and Open-Source

NeverMind doubles also a tool for memory researchers. To increase the impact of the project and increase the number of experiments that can be performed. Researchers that are interested in studying human memory in a non-invasive way can use NeverMind to conduct further experiments, because all the code for NeverMind is available and released in open source.

In this section, I suggest some ideas for further experimentation. I plan to run additional tests on the current versions of the interface to get additional insights on how space and movement can contribute to memorization.

Adding Input Layers to the Hippocampus Leads to Better Memory Recall

Through further testing, I plan to show how adding more layers of input to the spatial navigation mechanisms in our brain can lead to better memory recall. I intend to run a sequence of experiments that eventually lead to that point.

First, by testing exclusively for long-term retrieval with a list of items and isolating how memory recall behaves during a task encoded with images compared to navigation. Second, by incorporating imagery and check for performance. Third, by adding scene and context and topographic information with the imagery. Fourth, by combining augmented reality and movement. Fifth, by adding reward mechanisms during encoding tasks. Sixth, by adding auditory cueing during the encoding task and later reinforcement during sleep.

According to the general hypothesis, I expect to see a progressive increase in memory recall as more layers of the spatial navigation system are engaged and incorporated to the hippocampal map.

Test How Experiments in Humans Mirror Experiments in Rats

There are many behaviours that researchers have observed in rats but that for haven't tested on humans. However, there are many opportunities to take the experiments as an inspiration and perform a non-invasive variation for the experiments that have been shown to be successful in rats.

For example, taking Matt Wilson's experiment "biasing the content of hippocampal replay during sleep" [47] on rats as an inspiration, I'm interested in studying the relationship audio cueing during a spatial navigation task can affect memory recall. More specifically, I'm going to test how playing an audio cue during the memorization task and then replaying that in sleep, reinforces memory.

[47] Wilson, M. A. and Bendor, D. (2012). Biasing the content of hippocampal replay during sleep. *Nature Neuroscience*, 15(10):1439–1444

Test the for Maximum Single Shot Memorization

In the experiment described above, I tested NeverMind on lists of 10 items. Recall accuracy was nearly perfect (0.96) in the experiment, however, in future experiments I'm interested in concluding the maximum number of items a novice is able to memorize in a single shot using NeverMind.

Test How Movement Contributes to Memorization

In the "Preliminary Behavioral Experiments on Memory" section I described some early insights that preceded the design of NeverMind. The first insight suggested that the memory palace method is easy to learn if we use images of architecture that we have experienced and link them to a physically plausible path; showing that images of architecture combined with a cue can be used as effective memory palaces.

Recent neuroimaging studies of scene recognition have provided insights about regions that respond preferentially to pictures of scenes, landmarks and spatial layouts where three dimensional spatial information is depicted [48].

[48] Kanwisher, N. and Epstein, R. (1998). A cortical representation of the local visual environment. *Nature*, 392(6676):598–601

However, in NeverMind, participants walk along a physical route, allowing for full hippocampal engagement, which might lead to longer-lasting memories. The next step would be to compare the performance of the visual memory palace to NeverMind to understand how movement can contribute to memory formation and recall.

Test How Age Affects Performance

Future tests could include different age groups to measure and compare their performance. On the one hand, I'm interested in seeing how young children can use the interface to memorize in a playful way and seeing how an embodied and active method of memorizing might help them, for example, remember the multiplication tables.

On the other hand, I will test how seniors can use the interface to memorize content and compare their performance to other age groups. It has been shown that mnemonic training contributes structural changes in the aging human brain [49], so perhaps NeverMind could also be used in the context of a spatial memory training program.

[49] Engvig, A., Fjell, A. M., Westlye, L. T., Moberget, T., Sundseth, Ã., Larsen, V. A., and Walhovd, K. B. (2012). Memory training impacts short-term changes in aging white matter: a longitudinal diffusion tensor imaging study. *Human Brain Mapping*, 33(10):2390–2406

Test for Memory Duration

After finishing the experiment, I realized that participants remembered the content for much longer than anticipated. During the experiment, there was hardly any drop in memory recall, so I wasn't able to observe how content memorized with the interface fades. While experimental data wasn't collected, many subjects were able to recall the content memorized during the NeverMind task 6 months after completing the task. Next steps also include a long-term study on NeverMind to see how memory decays over time.

Identify Which Spaces Are Effective Supports for Memory

In the experiments, the locations and the visual cues were given to the participants. However, NeverMind allows for the users to pick their own locations for memory. This means that there is also the potential to study the spaces and locations people tend to use the most for memories and measure how effective they are. Insights from these experiments could be a first step in seeing how different environments effect memories differently and answering - what makes a space memorable?

Discussion

MIT STUDENTS WELL KNOW that Marvin Minsky famously said: "you don't understand anything until you learn it more than one way". In this section, I describe the interface from four different points of view. Each point of view is framed in the perspective of four figures whose work inspired this project: Matt Wilson, Marvin Minsky, Ed Cooke and Patrick Winston.

Today, the scientific community has no definite answer to why spatial navigation and memory are bound together, partly because of the inability to record brain activity while humans move freely through space. Following are four speculations on NeverMind from different lenses, plus an additional personal reflection.

Wilson Shows How Rats Memorize

The experiments Matt Wilson is doing in rats inspired me to conduct research on memory, space and movement. I met Matt Wilson in his office in November 2016 and shared the state of NeverMind as it was presented at UIST one month earlier. A central part of Matt Wilson's work focuses on the role of the hippocampus in episodic memory formation [50]. Following are some personal reflections on NeverMind after we talked.

[50] Foster, D. J. and Wilson, M. A. (2006). Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature*, 440(7084):680–683

Using a Cognitive Map as We Go

When people navigate through space, we are building a cognitive map as we go. We can take that map as a scaffold for memory. So, in fact, it is possible to reuse the locations where we have been and, since the links have been already established in reality, we can use that structure as a semantic map.

The hippocampus plays a key part for both memory and representation of space. The more inputs you provide to the hippocampus, the more robust the activation of the hippocampus becomes. More specifically, the hippocampus is involved in the formation of episodic memory as well as spatial memory used in navigation. First, in episodic memory, the hippocampus is responsible for the linkage of events; on the other hand, in spatial navigation, the hippocampus is responsible for linkage of spatial locations.

Taking into account recent research on the role of the hippocampus, I speculate that NeverMind might be taking advantage of the information our brain is subliminally encoding during spatial navigation and use the hippocampus's map as a frame for memory. In doing this it subconsciously engages the user in hippocampal activity, triggering episodic memory formation in tasks we normally use semantic memory for. This is done by pairing spatial navigation with visual cues with the memorization task, using an interface allow spatial and temporal engagement, guiding the way we memorize.

Using Imagery Combined With Navigation

NeverMind pairs spatial navigation and visual cues with the memorization task, using an interface allow spatial and temporal engagement, guiding the way we memorize. NeverMind is presumably engaging the user in hippocampal activity, triggering episodic memory formation for tasks we would normally use semantic memory. NeverMind takes advantage of the information our brain is subliminally recording during spatial navigation and uses the hippocampus' map as a frame for memory. NeverMind is presumably establishing hippocampal-dependent memory patterns that can be retrieved.

Compared to other mnemonic devices, what NeverMind does is taking away the demand for imagery and capitalizing the use of familiar locations, giving full engagement of spatial memory systems.

Levels of Spatial Navigation Machinery

In future work, I will test how different levels of immersion contribute to memory recall. The three levels could be: first, testing using flat objects, no 3d, simply an image of the visual cue; second, using VR to add virtual spatial information and presumably improving memory recall; third, using augmented reality, the most immersive option.

In sum, leveraging the systems that contribute to memory in a systematic way. The more inputs you provide to the hippocampus, the more robust the activation of the hippocampus is. So, a major contribution would be to build the curve up that shows how each level of immersion or hippocampal engagement contributes to memory recall.

What AR Brings: Differences with VR

In contrast to virtual reality, augmented reality presumably adds a strong sense of place that can come with movement systems. This combines the vestibular and path integration systems, bringing together all the spatial navigation machinery. Because augmented reality is movement based, it adds topographic and topologic activity that can contribute to a better memory recall.

Places vs Spaces

Wilson defines spaces are the world out there, whereas places are your experience in the world. Places are what forms the substrate for the systems that helps form episodic memories.

Memories of Locations

NeverMind is not only using memories of places; it is using memories of sequences of places, it is the linkages that occur when you move what makes the method unique. So, during recall, it is not about just imagining being in a place, it is about imagining when you move through space. The mental processes of imagining movement, compared to moving are different. In sum, movement provides a stronger input to the hippocampus to link together the locations.

In NeverMind you memorize sequences of items by moving through sequences of locations. Then, you can cue the item sequence by simply cueing the locations, using your experience of the sequence of locations.

The Importance of Movement

Other experiment ideas came from thinking about the importance of movement. Moving through space presumably engage a full set of capabilities of the hippocampal memory system. "Does the movement really add something? Experimentally no one has looked at that. If you give a rat a discrete exposure to locations, it would in principle activate. The continuity of movement, might be important for memory formation." Topologic memory requires certain connectivity, whereas topographic memory involves just things in space.

Using Reinforcement

Another potential idea for study is how the sequence memory encoding and retrieval might be affected by reinforcement. Experiments in rats show how engaging the reinforcement system might enhance recall and retrieval of specific memories, so perhaps a similar behavior is observed in humans. Reactivation is enhanced and biased, so experiencing a reward might lead to increased memory recall.

Cue Retrieval During Sleep

Further ideas for experiments include whether adding auditory cueing during spatial navigation in NeverMind, produces similar results to experiments performed in rats [51]. Next, during sleep playing back the sounds in sequential order. Then, checking whether memory recall is enhanced, leveraging the hippocampal retrieval systems that are activated during sleep. A possible hypothesis would be that more inputs to the hippocampus and subsequent evaluation increase recall.

[51] Wilson, M. A. and Bendor, D. (2012). Biasing the content of hippocampal replay during sleep. *Nature Neuroscience*, 15(10):1439–1444

Minsky and the K-Lines Theory of Memory

"K-lines: A Theory of Memory" [52], by Marvin Minsky changed the way that I think about human memory. K-Lines is a seminal paper because it predicts the important role of perception in understanding how humans deal with knowledge. Previous models have used the concept of knowledge representation to define how we learn about numbers, faces or sentences. However, they fail to address how we deal with feelings, insights or understanding. In this paper, Minsky describes a model that describes how we represent information internally, how we store it, how we retrieve it and how we use it. After reading K-Lines, I saw human memory from a new perspective, inspiring me to build a system that builds on experience to facilitate memory.

[52] Minsky, M. (1980). K-Lines: A theory of Memory. *Cognitive science*, 4(2):117–133

The Function of Memory is to Recreate Partial Mental States

Minsky identifies the function of memory as the capability to recreate states of mind. He suggests we remember methods, not answers. To support this idea, Minsky introduces the concept of knowledge lines: When you get a good idea you create a K-line for it. This K-line is then connected to certain mental agents that are active at that time. Then, when the idea is recalled the K-line is reactivated, stimulating the mental agencies that were active at it’s time of conception. The goal of this process is to recreate the original mental state. This idea tackles the problem of dealing with novelty in problem solving, that other models based on knowledge representation

K-Nodes, K-Lines and P-Structures

Next, he describes in detail a model of the mind that relies on perception. In Minsky's words, "feelings come before facts". He envisions the mind as an agglomeration of many autonomous agents (p-agents). These small p-agents, that can be either active or quiet, are grouped together in units called divisions. These divisions are responsible for sub specializations of different knowledge parts. Minsky names these perception structures (p-structures). In parallel, an intertwined network of k-lines and k-nodes are responsible for arousing the nearby agents in the memory recall process. The novelty of this model lines in explaining thought as multiple interacting agents rather than a logical consistent system.

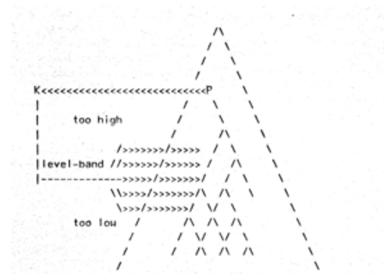

Figure 31: Diagram from the K-Lines paper illustrating how K-nodes are sensitive to other k-nodes that are "close to the memorable past but sensitive to the present".

Minsky is highly visual in his descriptions, even when writing about abstract concepts. For example, Minsky uses word "wires" when he refers to relationships, so the reader recreates the structure in his mind. Minsky uses analogies to describe complex relationships. He even labels the mental state of the highest order the Society of Mind, so the reader infers the internal dynamics automatically: "we will imagine first that this Mental Society works much like any human administrative organization" (Minsky, 1980), Minsky writes.

Using NeverMind to Draw K-Lines

So, if the function of memory is to recreate partial states of mind, how can we create memorable experiences to facilitate memory retrieval? In NeverMind, users remember a framework. When recalling content, the users are reenacting their mental state at the time of encoding. Because NeverMind users can answer questions about when and where they memorized the content, the interface facilitates the process of storage, encoding, and retrieval of memories.

Winston's Strong Story Hypothesis and Memory

From a higher-level perspective, the process of encoding and retrieval of memories can also be viewed through the lens of Patrick Winston's Strong Story Hypothesis [53].

[53] Winston, P. H. (2011). The strong story hypothesis and the directed perception hypothesis. *Association for the Advancement of Artificial Intelligence*

Storytelling Makes Us Human

The Strong Story Hypothesis holds that storytelling and story understanding is the key to human intelligence and the main difference between us and other primates (Winston, 2011). In this hypothesis, our ability to build complex, highly-nested symbolic descriptions enables us to tell stories. We are constantly telling, understanding, and recombining stories to reason, to plan and to educate. We tell stories when we think and we tell stories when we speak. (Winston 2017).

NeverMind Facilitates Storytelling

Through Winston's lens, in NeverMind, the user relies on experience and storytelling to facilitate memorization supported by imagination. During memory recall, the user is aligning to the sequences of events during the memorization process. Because the user has lived a specific event through experience, he is simulating the experienced paths and narrating the story of everything that happened and narrating the story of everything that happened.

Cooke Coaches a Journalist to Win the US Memory Championship

Another perspective came from Ed Cooke, a memory coach and a Grand Master of Memory. The Grand Master of Memory title is given to people that can perform these memory feats: first, memorize 1,000 random digits in an hour; second, memorize the order of 10 decks of cards in an hour; third, memorize the order of one deck of cards in under two minutes. Cooke was Joshua Foer's memory coach, who went on to become U.S. Memory Champion.

Cooke Trains Novices Using Memory Walks

I shared with Cooke the version of NeverMind that I presented at UIST. He described NeverMind as a "super interesting principle" and a "dream project." He sees it as a more fun, more enjoyable, and more engaging version of the memory palace - specially helpful for people that are getting started with the method.

Cooke pointed out how the project reminded him of the way he once taught novices to increase what their memories can hold. On Sundays, he used to gather a group of 30 people and go for "memory walks" around the London city center to help them get started with the memory palace. Cooke walked with a group and at each location told a short story to help them memorize specific content.

For example, when walking on a bridge, Cooke would tell people to imagine that seven swans are crossing in front of them. Then to retrieve the content later, they only needed to think about the bridge.

NeverMind Trains Novices Using Augmented Reality

Cooke recalls how making a method that relies heavily on imagination, experiential, made it easy for people to get started. NeverMind also aims to create a compelling experience for the user, but uses augmented reality technology for cues instead of a guide.

Rosello Uses Architectural Space as a Stage for Memory

If I close my eyes and think about it, I can still see it. I was sitting on the kitchen floor of a 70s apartment building. My thighs were resting directly against the terrazzo floor, absorbing the heat coming from my legs, translating in a cold sensation. The cold felt good, it was mid-august, and Barcelona can get burning hot in the summertime, close to the 100ths. The small window on the corner was open, but no breeze flowed through. Within an arm's length, I had a full stack of kitchen pots and pans that I used as an improvised drum set. Next to me, my partner in crime, Ignasi had already started banging one of the pots with a wooden spoon. The fluorescent light tinted the scene with a Matrix green hue. When I raised my head to look up, I could only see a tower of drawers before me. The room was narrow and deep and we were both sitting at the opposite end of the door. I was around one year old at the time, and this is my earliest memory.

Raising Spatial Awareness

NeverMind started from looking at space through an architectural lens. My memories have always been spatial in nature; when I think back about my most memorable experiences, there is always a strong spatial component associated with it. When we recall past events, it's rarely a single element that emerges, but rather a network of thoughts that start to recreate a scene in our heads. Noticing that the spaces we live in are a stage for our memories was probably the key insight that drove the project forward.

When I started developing NeverMind, I was excited about changing the experience of memorizing. How we could combine the spaces that are memorable to us and help people remember the content they intend to remember, and along the way hopefully changing the way people think about architectural space.

And also, from an architectural point of view, I was interested in understanding why certain spaces are more memorable than others. Are certain spaces universally more memorable? And if so, how can I gather insights to be able to design memorable places? Hopefully, NeverMind is a step towards that direction.

Future Work

In this section, I explain ideas and current work in progress for future versions of NeverMind.

Mixed Reality Version

I'm planning on implementing a mixed reality version of NeverMind. At the moment, the graphical content supplied by the interface is not anchored to a specific spatial location. When the user approaches the target location, and the user taps the system to retrieve an image. This means that the augmented reality images move with the user's head motion. I speculate that that anchoring images accurately with reality will lead to more memorable results.

Support Other Sensory Information

I plan to show how adding more layers of input to the spatial navigation mechanisms in our brain can lead to better memory recall. For this, I will develop a flexible platform that can host other sensory input, including audio and scent. More specifically, I'm going to test how playing an audio cue during the memorization task and then replaying that in sleep, reinforces memory.

Video Review

Future features of NeverMind include video recording during the memorization task for later replay, allowing revising or studying the content of the palace without the need of being physically there. A first implementation will include a recording of the routes as the user sees them with overlays of the images to remember. This would result in a video that could be played at 10x speed, slowing down when the content appears and resembling memory consolidation that goes on through the REM phases of sleep. The video should be easily played forward and backward to help the memorization process.

Knowledge Playlists

In the current version of NeverMind, "knowledge playlists" are user specific, but there is potential for it to be shared with other users. I propose to create a social platform to the share and download knowledge with friends or classmates. Each user can use their own palaces and populate them automatically with content downloaded from the web. Predefined graphic associations could be built in, and the user could alter the content. This would build a database of concept-image pairings sourced from the community of users. Experiments with the current version of NeverMind show that the content can be shared among different users with promising results. Potential applications of this feature include bootstrapping content into the student's memory before class.

Chunking the Palace

Controlling image placement accurately would also open up new features of the interface. For example, adding hierarchy to the palace instead of just sequential information. With this feature, the user could control the amount of detail the user wants to remember. This would lead to remembering a set of concepts at different levels of hierarchy. The essential content could be recalled just enough to make a 30-second elevator pitch to an investor, more details could be added to make a 7-minute Pecha Kucha presentation, or if we recall all the content, we could deliver a 20-minute presentation on an idea.

Google Street View Version

Early experiment insights have shown that images of places we know could also be effective supports for memory. If this is the case, we could develop an interface where users program a route using Google Maps and then can train on a Google street view version of the palace. This implementation would use places that are familiar to the user without physical spatial navigation.

Integrated Augmented Reality Mobile Phone App

If we want to make the memory palace accessible to a wide-audience, then it makes sense to use hardware that is already available to everyone. Another version of the interface could run entirely on your mobile phone. Conceptually, the project would be similar to the PokemonGo App, but instead of picking up creatures from your living room, the user could drop memories at specific locations and later retrieve them by using augmented reality.

Contributions

Human-Computer Interaction

I suggested we can increase human potential through interfaces, by describing the concept of the symbiotic interface and using it to augment human memory. I designed and tested NeverMind, an augmented reality (AR) interface to support memory that works by pairing visual cues with spatial navigation during the memorization task. I showed one way AR can support long-term memorization and made a memory champion technique accessible to anyone.

Human Intelligence and Artificial Intelligence

I suggested that we can use interfaces to reveal insights on human intelligence, in the context of memory augmentation and developed a biologically inspired learning model for memory. I helped users memorize sequences of items in one-shot, facilitated by NeverMind, and conducted experiments which show that recall rate is nearly-tripled compared to paper-based methods. Further, I provided an open-ended platform for future episodic memory research.

Learning Sciences

I designed an on-the-go technique to help users memorize efficiently and enjoyably, where users engage both in physical space and visual tasks. NeverMind users learned to learn through experience, guided by an interface. I showed how simultaneous engagement of spatial navigation and visual processing facilitates learning, revealing a process we can all do as an alternative to repetition.

Architectural Design

I showed how architectural space can be used as a support for people's memories and raised awareness on the importance that architecture has for them. Finally, I provided a platform for research that could help answer the question of what makes a space memorable.

Software and Demo

- Open-Source Code of the NeverMind iPhone App:
  `https://github.mit.edu/rosello/NeverMind`
- Open-Source Code of the NeverMind Moverio AR Headset App:
  `https://github.mit.edu/rosello/NeverMindAR`
- Video demo of NeverMind:
  `https://vimeo.com/199716617`
- Short paper on NeverMind presented at ACM's UIST '16:
  `http://dl.acm.org/citation.cfm?doid=2984751.2984776`

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