Designing a Novel Brain Computer Interface to Improve Cognitive Functioning in Older Adults with Mild Cognitive Impairment Using Auditory Stimulation During Slow-wave Sleep

How do Technologies Targeted Toward People Living with Alzheimer's Fit Into Theoretical Care Models which Promote Humanism and which have also been used to Design Care Facilities?

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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General Research Problem: Designing for People Living with Alzhiemer's

How can we design technologies to suit the needs of people living with Alzhiermer's?

Alzheimer's Disease (Alzheimer's), a currently incurable degenerative brain disease that progressively affects patients' memory, thinking, and behavior over time, affects 6.5 million Americans over the age of 65. In 2022, the cost of care for people 65 and older with Alzheimer's and other related dementia conditions was $321 billion. 65% of that cost came from Medicaid and Medicare and a quarter came from out-of-pocket. 35% of people living with Alzheimer's live in some type of care facility. 75% of those over the age of 80 with Alzheimer's live in a nursing home and most will live out the rest of their lives there (*2022 Alzheimer's Disease Facts and Figures*, 2022). The projects to be described aim to understand how we can best serve this massive demographic and use that knowledge to have an impact on that demographic by developing a novel, wearable device.

Currently, there are only five FDA-approved medications that attempt to treat Alzheimer's, four of which only target symptoms and all of which have undesired symptoms (Yiannopoulou & Papageorgiou, 2020). Cognitive therapies and music therapy have emerged in recent years as promising treatment options but both have inconclusive results (Carrion et al., 2018; Na et al., 2019). However, recent studies on the efficacy of auditory stimulation during sleep to improve cognitive performance and memory consolidation, especially in individuals with mild cognitive impairment (MCI), have shown positive results (Papalambros et al., 2017; Papalambros et al., 2019). Previous devices brain-computer interfaces (BCIs) have been made which can enact auditory stimulation after detecting EEG (electroencephalogram) signals, electrical activity in the brain, of a predetermined frequency and amplitude. Designing this type of BCI device for older patients with either MCI or early onset Alzheimer's through a person-centered approach may be a good way to serve those populations.

Developing one technology is only part of the solution. There is a vast literature on how shaping the environment of care facilities, the building layouts or items within them, can improve the standard of living for people living with Alzheimer's. We should strive to understand other technologies targeted toward people living with Alzhiemer's, such as care robots and video conferencing devices, and specifically how those technologies fit within the environments people living with Alzhiemer's reside in. This will improve future developments of those technologies. It will also help us consider when and how to introduce those technologies into their environments. If we are able to design technologies that fit the needs of people living with Alzheimer's, we could see better health outcomes for residents, higher standards of living, higher standards of care, and considerations of safety, autonomy, and community.

Development of an Auditory Stimulation Device to Improve Cognitive Function and Memory Consolidation.

What is the most marketable form factor design for a wearable auditory stimulation device for older adults with mild cognitive impairment, and how can a phase-locked loop design be used to detect slow wave sleep and correctly activate auditory stimulation to enhance slow wave sleep?

There have been many proposed ways for brain-computer interfaces that can influence the brain. In the 2000s, there was a focus on using direct currents to stimulate the brain (Annarumma et al., 2018). Starting in the late 2000s and early 2010s, researchers also attempted to use odor to stimulate brain activity (Sowndhararajan & Kim, 2016). In the past decade, auditory stimulation has emerged as an alternative, non-invasive way to stimulate the brain (Santostasi et al., 2016). However, currently there has been no successful commercial auditory stimulation BCI targeting geriatric populations, specifically those with MCI or Alzheimer's. Auditory stimulation works through either bone conduction or direct stimulation through the ear. The mechanism is poorly understood but correctly stimulating the brain is believed to be correlated with increased cerebrospinal fluid flow which can clear Beta-amyloid plaques, the main culprit that causes Alzheimer's (Han et al., 2021). Research has shown that correctly stimulating the brain to improve memory consolidation means amplifying slow-wave sleep (SWS) (Santostasi et al., 2016). Also called N3, SWS is the stage of sleep that occurs before rapid-eye movement (REM) sleep. It consists of brain waves that have low-frequency delta waves (0.5-4 Hz). These waves have been thought to transmit information from the hippocampus to the frontal cortex for memory consolidation (Tang & Jadhav, 2019). Correctly stimulating these slow waves means activating auditory stimulation during the up state, part of the wave that has a positive voltage, to increase its amplitude (Cox et al., 2014). There have been minor successes in using auditory stimulation to improve memory consolidation in younger and middle-aged adults (Diep et al., 2018, Diep et al., 2019). Recent studies show that this method can be used to enhance memory consolidation in older adults with MCI (Papalambros et al., 2019).

To this extent, we aim to develop a novel, wearable auditory stimulation device targeted towards older adults with MCI. By specifically targeting this population, we hope to improve cognitive functioning and memory consolidation and thus improve their clinical outcomes and ability to perform everyday tasks. A major hurdle is that the sleep architecture of individuals changes as they age (Edwards et al., 2010), so a specific design is needed both in the physical form but also for the software. Recently, the phase-locked loop (PLL) design has become prevalent. It is a control system that generates output signals, in this case auditory stimulation, of the same phase as the input signal, the EEG signals. Specifically, the goal will be to time auditory stimulation events to be in sync with the peak of the up state in the EEG signals, which is essential in enhancing the up state and SWA (Santostasi et al., 2016). We aim to utilize a PLL design specifically targeted toward the sleep architecture of older adults with MCI.

Methods

The first goal is to design a form factor for the device. The initial constraints of the form factor will revolve around the hardware being used in the device. Currently, we will be using a Hypnodyne or similar device, which will be incorporated into the form factor. The Hypnodyne can read EEG waves, the electrical activity generated in the brain, from users and transmit the data to a wireless receiver, currently attached to a USB drive. The wireless USB will also be able to transmit actions to the device using the received data. This is where the PLL software program will be utilized. In brief, the program will be able to read live EEG data, determine if the user is in N3, and be able to send a signal to the wearable device, to stimulate the user with pink noise, random noise having equal energy per octave, using some type of audio device also incorporated into the form factor. The time point of the stimulation will coincide with the upstate of the slow wave adjusted for signal lag. Previous studies have used a 20-degree phase adjustment before the peaks of upstate slow-wave sleep waves (Papalambros et al., 2019; Santostasi et al., 2016). The pink noise stimulation will most likely be 50 ms bursts to be comparable with previous research (Papalambros et al., 2019; Santostasi et al., 2016). Parameters will be adjusted to determine if a user is in N3. These parameters include duration in the phase, the amplitude and frequency of the EEG waves, and presence of non-N3 sleep structures (alpha waves, beta waves, sleep spindles, k-complexes). We will develop this system using LabView, which will also be used to analyze data live. We currently have a large EEG sleep wave data set we will use to analyze and create the PLL algorithm. We also plan to conduct a study on patients with varying cognitive impairments in short-term sleep study using the prototype devices to assess its efficacy. This study will also include interviews and an assessment of prototype usability. These studies will be used to iterate on the device for improvements. Interviews will also be conducted initially to develop a form factor so the design can be targeted to older adults with MCI. Some design considerations may include comfortability, willingness of users to use, and ease of use. Another design constraint to be considered is the number of electrodes. Ideally, one is needed for the frontal lobe, which provides the best slow-wave signals, and at least one other electrode is placed on the head as a reference (Botella-Soler et al., 2012). The electrode amount and placement will need to be considered when designing the form factor.

The result should be a functional device with a form factor suited for older adults with MCI and a functional PLL design that can effectively enhance slow wave sleep to improve memory consolidation. This device will hopefully be put into the marketplace and be used to slow the onset of Alzheimer's and improve the lives of older adults with MCI.

Implementing Technologies into the Environment of People Living with Alzheimer's

Are technologies targeted towards people living with Alzheimer's compatible with theoretical frameworks used by care facilities that promote humanistic principles?

In 1978, the scientific community eliminated the age distinction between Alzheimer's Disease and senile dementia, making Alzheimer's Disease a major public health issue (Lacey, 1999). Historically, nursing homes had refused residents with dementia before the 1980s. However, Mental Institutions started denying patients with Alzheimer's dementia since it was classified as a disease and not a mental illness in 1978. This led to the development of Special

Care Units (SCU) in nursing homes in the 1980s. These SCUs placed residents in poor conditions with high use of physical restraints, tranquilizers, locked doors, and alarm systems. Even after the passing of a 1987 Omnibus Reconciliation Act, at the urging of the Institute of Medicine, failed to completely reform nursing home care. It succeeded in reducing the use of restraints and tranquilizers but saw mixed results with respect to how specialized the care was or if it was just a means of segregation (Lacey, 1999). In the 1990s and past, there has been steady reform with focuses on humanistic principles, which value individualism and personal worth. This included the development of assisted living facilities. These assisted living facilities were designed to emulate the home environment, housing 10-12 residents with trained caregivers (Calkins, 2018). Throughout the years, there have been many models proposed on how Alzheimer's patients should be treated. This includes models of what a long-care facility environment should look like: Eden Alternative, Wellspring, Greenhouse, and Lakeview (Gaugler et al., 2014). But it also includes theoretical models of how to treat people living with Alzheimer's: Social Re-engagement (Lacey, 1999) and Person-Centered, a humanistic approach used in the previously mentioned facility models (Calkins, 2018). This research project aims to understand if technologies such as care robots and video conferencing devices targeted towards people living with Alzheimer's are compatible with these two theoretical models. Important factors that will be researched are how these models and technologies tackle problems about safety, autonomy, security, community, and treatment. Environments and technologies should be shaped for the betterment of residents, but caregivers, visitors, and community members will all be interacting with these spaces and technologies as well, so their presence will also be considered.

An important part of the progression of humanistic principles in the care of people living with Alzheimer's was the culture-change movement. This movement innovated the design of nursing homes in the US. The models include the Eden Alternative, the Wellspring model, and the Green House design. These models have generally tried to change nursing home environments to be more home-like, with more outdoor space, and walking areas (Gaugler et al., 2014).. One of the biggest approaches to Alzheimer's care has been person-centered care, where a patient actively participates in their treatment. Person-centered care stresses respect for patient individuality and meaningful engagement. With respect to the environment, person-centered care proposes many design features that attempt to empathize with Alzheimer's resident's reality while trying to balance autonomy and safety of the individual (Calkins, 2018). It values choice, proposing that residents should be able to decide if they wish to live integrated with older adults without dementia or wish to live segregated, even though some studies claiming segregated communities may be worse off (Marquardt et al., 2014).

There are many technologies being developed to improve the lives of people living with Alzheimer's. These technologies include social/helper robots, social apps, GPS apps, reminder/scheduler apps, entertainment/engagement apps, and videoconferencing technologies (Koumakis et al., 2019). The implementation of these technologies ask questions about the value of human interaction, in-person or online. Adding these technologies to an Alzheimer's resident's living environment, specifically referring to technologies that have a physical presence (ei. robots, cameras, and video conferencing devices), could have both positive and negative impacts. Person-centered care would ask if these technologies were even wanted by their user or if there is a choice in how they utilize them.

Methods

Research will be conducted by reviewing the literature of theoretical frameworks used to design care facilities, to first understand how others have tackled developing living environments for people living with Alzheimer's. Then, technologies currently being marketed as care robots and videoconferencing devices targeted toward people living with Alzheimer's will be analyzed to understand if these technologies have been developed in a manner which fits into these models. The first part of this research will be analyzing literature on these technologies for their clinical effectiveness or effectiveness in improving standards of living. The design specifications of those technologies will also be analyzed to determine if use by individuals with Alzheimer's or their caregivers was considered in the device designs. Customer reviews will also be researched to understand how users feel about the technologies: how willing they are to use them, what are their preconceptions about their uses and effect, and how easy do they think they are to use and integrate into their lives. Ads of these technologies will be researched to understand how companies view their target users. Lastly, interviews will be conducted with older adults with MCI to understand how they view these technologies and how they see them in the environment they live in.

Conclusion

From this research project, I hope to understand how to design technologies for people living with Alzheimer's. Understanding these design principles will help to design an auditory stimulation device targeted toward older adults with MCI that will be marketable to them.

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