WHITE PAPER

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humm
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Introduction

For millennia humans have lived in the dark, not knowing that our thoughts and our lives were controlled by one of the most complex systems in nature that sits just above our shoulders. But times are changing and, over the last thirty years, incremental discoveries in neuroscience have opened new horizons in our understanding of the brain’s inner workings. New technologies are now emerging that allow us to improve the health and performance of our brains, redefining what’s possible for how we experience and enjoy our lives.

At Humm, we envision a world where these new technologies improve the daily life. Our long-term mission is to replace all the supplements, medications and other tools that people use to improve their brain with healthier, better technology that nurtures and improves our mental capabilities. Today we are a startup seeking to merge the best in neuroscience research and advanced technologies to create a consumer product that makes learning easier.

Learning is one of the greatest sources of joy in life, and the times in our lives where we learned the most are often remembered as our happiest and most liberating. The goal of our first product, the Humm Patch, is simply to make learning easier for everyone - so that we can all continue to grow, adapt and make the world a happier place. The Patch adopts a method known as transcranial alternating current stimulation (tACS) developed by neuroscientists at some of the world’s leading medical and research institutions. In this White Paper, we’re pleased to present some of the exciting results observed in those labs, as well as our own placebo-controlled trial and broader user-experience testing.

In building the Humm Patch, we’ve been privileged to stand on the shoulders of two generations of scientists and entrepreneurs who have developed neurostimulation devices for medical and consumer purposes over the last thirty years. Indeed neurostimulation devices are already commonplace for the treatment of some common neurological disorders, and there have been several consumer devices targeted at the financial and technological elite. Unfortunately, however, these devices have universally been expensive, bulky, unintuitive and intimidating. And so, in developing Humm for a much broader cross-section of society, it was clear to us that there was an urgent need to improve upon the cost, approachability and ease of use of anything that had come before. For that reason,
we have substantially reinvented the user interface of this tACS technology, as the last section of this paper details.

The Humm Patch represents an important first step, allowing us to help tens of thousands of people live happier, healthier lives while we further develop. Over the next several years, we will continue to research and improve the core technology, extending our focus beyond learning into other important cognitive functions and even the treatment of neurological disorders. We’re deeply inspired by some of the exciting early work going on in the field pursuing such outcomes as a treatment and even cure for Alzheimers, rapid rehabilitation of traumatic brain injuries and of course the realization of science fiction’s grand ambitions for direct brain-computer interface for such important tasks as instantly learning kung-fu.

Our team comes from disparate backgrounds in neuroscience, medicine, business and engineering, but we’re united by a passion for empowering people to live better lives by using their brains. We’re proud to have been founded in Perth, Western Australia and now headquartered in Berkeley, California, working with researchers and investors in the area. If you think like we do, join us on our mission.

Think better.

- Iain, Tim and Ahmud; founders of Humm.

thinkbetter@humm.tech
Scientific Background

Humm builds upon decades of research into transcranial electrical stimulation.

Humm has developed and tested novel technology building upon existing transcranial electrical stimulation (tES) research, a method of non-invasive brain stimulation that has been demonstrated to modulate neurophysiological activity and cognitive state. tES has been used therapeutically since its initial FDA approval for depression, anxiety and insomnia in 1979. The method has been extensively studied with more than 4,000 peer-reviewed publications available, and industry standards have been developed to regulate the design and application of such devices.

Several forms of tES exist, each using slightly different techniques (Fig 1). The most common forms of tES are transcranial direct current stimulation (tDCS), transcranial random noise stimulation (tRNS); and most recently, transcranial alternating current stimulation (tACS). Each of these techniques uses slightly different stimulation parameters to achieve a variety of physiological effects.

tES operates principally through subthreshold modulation of neuronal membrane potentials, altering cortical excitability and activity, in order to produce cognitive and behavioral changes. Other relevant physiological effects include changes in neurotransmitters, microvessels, inflammatory processes and glial cell function.

tES modulates spontaneous neuronal activity and consequently the size and duration of its effects depend on the baseline state of the target neurological structures. This is in contrast to techniques such as transcranial magnetic stimulation (TMS) and paired associative stimulation (PAS) which induce synchronized discharge of action potentials in the target neural tissue.

![Fig 1. Example waveforms of different tES techniques.](image-url)
changes the threshold for discharge of stimulated neurons, and therefore their likelihood of firing.\textsuperscript{3,5}

Importantly, tES is polarity dependent.\textsuperscript{3,11-13} Anodal stimulation refers to the application of a positive current whereas cathodal stimulation applies a negative current to the target area.\textsuperscript{13,14} The response of an individual neuron to this current then depends on its distance from the electrode, its orientation relative to the electric field and its morphology.\textsuperscript{3,11-13} Pyramidal neurons in the cerebral cortex are oriented perpendicular to the scalp, and therefore typically lie parallel to the applied electric field, which causes a shift in their resting membrane potential (Fig 2).\textsuperscript{3,13,15} As the field strength increases, the membrane voltage has been found to increase linearly until the point of action potential generation.\textsuperscript{13}

Current is usually applied at an intensity of up to 2\text{mA} with electrodes of 16-35 cm\textsuperscript{2} surface area.\textsuperscript{17} In cadaver models, the applied current is roughly halved by the skin and soft tissue, then attenuated another 16\% by the skull, before reaching the brain.\textsuperscript{18} Despite this, tES has been found to reliably produce electric fields deep within the brain in a dose-dependent and montage-specific manner.\textsuperscript{19}

tES also affects intracellular ion concentrations, neurotransmitter release and neuromodulator concentrations to enhance neuroplasticity.\textsuperscript{13} Anodal stimulation was found to increase intracellular Ca\textsuperscript{2+} concentration, driving short and long-term plasticity.\textsuperscript{12,13,20,21} There is strong evidence that tES influences neurotransmitter concentrations through action potential propagation and vesicle release probability.\textsuperscript{13} tES also appears to modulate mood through the serotonergic system, as well as skill learning through brain derived neurotrophic factor (BDNF) dependent neuroplasticity.\textsuperscript{13,22} Both of these effects, however, may vary between individuals due to genetic polymorphisms.\textsuperscript{13,23,24}
tACS has been shown to modulate the brain’s electrical activity.

Humm utilizes tACS, a form of tES that has been demonstrated to modulate a variety of cognitive functions, such as multitasking performance, response time, working memory and long term memory. tACS appears ideally suited for noninvasive modulation of brain activity, having been shown to influence endogenous oscillatory electrical activity. These synchronous oscillations of large populations of neurons, detected with electroencephalography (EEG) and widely referred to as ‘brainwaves’, represent highly organized brain activity.

Specific oscillatory frequencies emerge in EEG recordings dependent on the task being performed, the state of the subject, and the brain area being recorded. For example, alpha oscillations (8-12 Hz) recorded over the occipital cortex are thought to inhibit task-irrelevant visual processing, whereas synchronization of theta oscillations (4-8 Hz) between the frontal and parietal cortices is thought to be critical in the maintenance of attention and working memory. Similar patterns in oscillatory activity are also well characterized in a number of psychiatric and neurological disorders.

tACS is thought to modulate electrical activity through both entrainment and resonance effects, having been found to shift the frequency, phase and power of neuronal firing in vivo, in vitro and in computational models. Entrainment refers to the synchronization of the frequency and phase of neuronal activity to an external stimulus. Resonance effects refer to the amplification of a network’s activity by stimulation at its dominant endogenous frequency. tACS is thought to produce both of these effects by altering the likelihood of neuronal firing in an oscillatory pattern, thereby recruiting a larger population of neurons into task-relevant rhythmic firing networks, increasing the oscillatory power at

![Fig 3. Influence of tACS on local field potential and neuronal firing.](image-url)
the targeted frequency and augmenting the network activity (Fig 3).\textsuperscript{15,26,36} Importantly, single neuron recordings have demonstrated that tACS is able to entrain neural activity while scalp somatosensory input is blocked with topical anesthetic.\textsuperscript{38} This indicates that peripheral nerve stimulation is not required for cortical entrainment, consistent with tACS having a direct effect on the cortex itself.\textsuperscript{38}

In general, particular cognitive functions are performed by distributed brain networks, with cortical sub-regions performing sub-computations of these functions.\textsuperscript{26,28,39} Oscillations within brain tissue selectively enhance transfer of information through these networks.\textsuperscript{26,28,39} tACS is thought to increase neuronal enlistment in the cortical region targeted by the electrode.\textsuperscript{26} As neurons are more likely to fire in response to each other when their depolarizations are synchronized, the increased coherent activity produced by tACS is thought to enhance information transfer and processing within the targeted network.\textsuperscript{26,40} As such, tACS could establish ‘coupling’ between brain regions, increasing network efficiency and altering cognitive function.\textsuperscript{26,39} In support of this, Polanía et al. reported decreased reaction times in a working memory task during synchronized (0° phase offset) 6 Hz tACS applied to the left frontal and parietal lobes, whereas reaction times increased during desynchronized (180° phase offset) stimulation.\textsuperscript{41}

**Frontal midline theta is critical to working memory and attention.**

Neural oscillations in the theta frequency range (4-8 Hz) are crucial for the functioning of normal memory and attention.\textsuperscript{42} In particular, prominent 6 Hz signals recorded from the prefrontal cortex (PFC) along the midline, known as frontal midline theta (FMT) can be induced by various mental tasks.\textsuperscript{42,43}

FMT is generated in the bilateral prefrontal cortices, including the dorsal anterior cingulate cortex (dACC), as confirmed in magnetoencephalography (MEG) studies (Fig 4).\textsuperscript{42,44-47} FMT is known to be closely associated with PFC-dependent cognitive tasks, coinciding with processes such as working memory, episodic encoding and retrieval, mental arithmetic, error processing and action monitoring.\textsuperscript{42,46-60} FMT is thought to provide a general mechanism for the PFC to establish network connections to other brain regions.\textsuperscript{42,60,61}

FMT is thought to be responsible for maintaining and manipulating the information held within working memory in the absence of external stimuli, and is known to increase in
power with memory demands.\textsuperscript{42,43,62} FMT has been found to decrease in power during times of acute stress, being associated with impaired cognitive performance.\textsuperscript{42,63} Additionally, older adults have been found to exhibit reduced frontotemporal theta synchronization, associated with impaired working memory performance.\textsuperscript{64} FMT also exhibits a negative relationship with default mode network activation, and may be involved in focusing attention on task demands while inhibiting irrelevant information.\textsuperscript{42,65,66} It has been used successfully as a measure for monitoring athletes’ mental state during sports performance.\textsuperscript{67}

\begin{itemize}
  \item Polanía et al. (2012) found synchronous left frontoparietal 6 Hz stimulation improved reaction times in a visual WM task, whereas anti-phase stimulation worsened performance and increased reaction times.\textsuperscript{41}
  \item Meiron & Lavidor (2013) demonstrated an increase in verbal working memory accuracy using anti-phase bifrontal 4.5 Hz stimulation.\textsuperscript{68}
\end{itemize}

\textbf{Theta tACS has been shown to improve working memory, attention and multitasking.}

Theta band tACS has been demonstrated to modulate dACC activity in a frequency-dependent manner, and has been found to increase multitasking performance, attention, working memory and short term memory (STM) span.\textsuperscript{42,64,68-72}:

\begin{itemize}
  \item Polanía et al. (2012) found synchronous left frontoparietal 6 Hz stimulation improved reaction times in a visual WM task, whereas anti-phase stimulation worsened performance and increased reaction times.\textsuperscript{41}
  \item Meiron & Lavidor (2013) demonstrated an increase in verbal working memory accuracy using anti-phase bifrontal 4.5 Hz stimulation.\textsuperscript{68}
\end{itemize}
• Jaušovec et al. (2014) determined subjects’ individual alpha frequency, then applied synchronous theta stimulation 5 Hz lower than this frequency. Stimulation of the parietal areas improved WM capacity while left frontal stimulation had no significant effect, suggesting a central role for the parietal region in WM capacity.  

• Hsu et al. (2017) used anti-phase bifrontal 6 Hz stimulation to demonstrate an improvement in multitasking performance, coupled with significant modulation of posterior beta activity. Subjects with greater increases in frontal theta, alpha and beta power exhibited greater improvements in multitasking performance.  

• Violante et al. (2017) used synchronous right frontoparietal 6 Hz stimulation to demonstrate an increase in verbal WM response times during tasks with high cognitive load. fMRI data revealed that tACS increased parietal activity, which correlated with WM improvement.  

• Reinhart & Nguyen (2019) demonstrated that age-related cognitive decline and working memory deficits are associated with reduced frontotemporal theta synchronization and reduced temporal theta-gamma phase amplitude coupling. Individualized theta tACS was then demonstrated to eliminate the age-related impairment in working memory accuracy and restore theta-gamma coupling in older adults. These effects occurred rapidly and persisted beyond the completion of stimulation for approximately one hour following the session, after which measurement was ceased.

**tACS is safe with no serious adverse effects.**

No serious adverse effects have been observed in scientific studies. tACS is effective at low currents and can be reliably used below the threshold of skin perception, reducing the likelihood of minor side effects such as itching, tingling and erythema.

Charge density, a combined measurement of current, electrode surface area and stimulus duration, is an effective tool for determining the amount of charge present in a specific area. Using measurements of charge density, Liebetanz et al. (2009) determined that physical damage to the brain, such as lesions, began to occur after the charge density threshold of 52.40 kC/m² in rat models. As a comparison, human studies with tDCS, which generally administer low levels of currents for short periods of time and through larger electrodes, tend to have a charge density of <1 kC/m². The total charge density applied by Humm over a session of stimulation is comparatively smaller still, due to the
sinusoidal waveform applied. As such, the dosage of charge administered presents a minimal risk of physical adverse effects.

No significant temperature increases have been predicted or observed from tES. In comparison, fifteen minutes of cell phone usage may increase the temperature of brain tissue by approximately 1°C. The power dissipation from tES into the brain (0.1 mW/kg) is four orders of magnitude lower than that from a cell phone (1.6 W/kg), and five orders of magnitude less than the metabolic heat production of the brain itself (11 W/kg). Heating effects on the brain during tES are therefore insignificant.

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<tr>
<td>Maximum legal specific absorption rate in brain from cell phone</td>
<td>1.6 W/kg</td>
</tr>
<tr>
<td>Average power dissipation in brain from 1 mA tES</td>
<td>0.1 mW/kg</td>
</tr>
<tr>
<td>Metabolic heat production of brain</td>
<td>11 W/kg</td>
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*Table 1. Power dissipation of tES.*

Although persistent or physical adverse effects have not been found, minor temporary adverse effects may include visual artefacts, cutaneous perceptions, pressure sensation, heat sensation, dizziness, tingling, itching, induced headaches and general discomfort. No increase in the incidence of adverse effects has been noted with ongoing use.

Benign visual artefacts, such as phosphenes, are often perceived at frequencies of 10-20 Hz, peak at a frequency of 16 Hz, and stop being observed at a frequency of greater than 40 Hz. In addition, visual artefacts are more common in electrode montages placed anteriorly on the head and less common in posterior electrodes, suggesting that phosphenes are of retinal rather than cortical origin. Cutaneous perceptions are reported more commonly at low frequencies of stimulation, with over 70% of participants reporting perceived sensations at 20 Hz and less than 30% reporting at over 140 Hz in one study.

Cognitive off-target effects from tES have been reported by one study to date. Iuculano & Kadosh (2013) found numerical learning speed was improved with posterior parietal cortex tDCS but with an associated impairment in automaticity, and vice versa with dorsolateral prefrontal cortex tDCS. Although these results cannot be generalized and may be specific to the montages used, it raises an important consideration about the
potential costs of enhancing particular cognitive functions. Broader cognitive assessment is recommended in future studies to screen for the possibility of cognitive trade-offs.

Reports for itching, tingling, headaches, discomfort and burning perception have been explored through the use of sham versus verum tests in double blind experiments. Some effects such as itching (~39%) are reported much more commonly than others, such as perceptions of burning (~8%) in case studies. However, no significant difference in the incidence of adverse effects has been found between sham and stimulation groups.
Clinical Trial

Humm has demonstrated a significant enhancement of working memory performance in a randomized, double-blind trial.

Forty subjects were recruited for participation in a double-blind, randomized controlled trial to measure the effects of Humm on working memory in comparison to sham. A mean increase in maximum working memory capacity of 19.82% was observed during stimulation, an improvement 120 times greater than the natural learning effect observed in the control group. These differences became even more pronounced following the completion of stimulation.

These results further substantiate evidence from the existing literature of the influence of theta band tACS on working memory performance, demonstrating significant validation of the efficacy of Humm and providing a foundation for further development of the underlying technology.

Materials & Methods

Participants

Forty healthy adults were recruited from the general population using online advertising and message boards. Of this group, three participants were excluded due to dropout and one was excluded as an outlier after displaying results more than 3 standard deviations higher than the group mean, frequently achieving the maximum score possible in the psychological test employed. No other participants were familiar with the style of test used. The remaining 36 participants (mean age: 26.4 years, range: 18-56 years, 29 males)

<table>
<thead>
<tr>
<th></th>
<th>Mean Age</th>
<th>Std Dev</th>
<th>Min Age</th>
<th>Max Age</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>25.9</td>
<td>10.1</td>
<td>18</td>
<td>56</td>
<td>14</td>
<td>4</td>
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<tr>
<td>tACS</td>
<td>26.9</td>
<td>7.7</td>
<td>17</td>
<td>56</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. Participant demographics by group.
were randomly assigned into the tACS group (mean age: 25.9 years, range: 18-56 years, 14 males) or a control group (mean age: 26.9 years, range: 17-56 years, 15 males), to which the experimenters were also blinded. All participants provided their informed consent prior to commencing.

**Experimental procedure**

Fig 5 illustrates the experimental procedure. Tests were undertaken by each participant in a single session. Participants completed three test batteries, each consisting of five individual Corsi block-tapping tests. Each battery was of approximately 10 minutes duration and separated by a 3 minute break. The initial test battery was performed as a baseline measurement.

Participants in the tACS group received stimulation from immediately after the completion of the first test battery until shortly after completion of the second battery, for a total duration of 15 minutes. Participants in the control group received only a control stimulation for this same period. Participants began the second test battery 3 minutes after commencing stimulation.

Prior to commencing testing, participants were asked to rate on a scale from 1-10 their expectations for the likelihood that stimulation would improve their scores, with 1 being highly unlikely and 10 being highly likely. After completion of testing, participants were asked to rate their perceived benefit from stimulation using the same scale.

**Experimental paradigm**

The Corsi block-tapping test is a traditional visuospatial working memory task. Blocks are displayed on a computer screen, which light up in a randomized order (Fig 5). A
reverse Corsi test was used, in which participants must reproduce the sequence in the reverse order in which they appear. Each test began with a three-block sequence, which was then increased by one item following a correct response. Each test continued until an incorrect response was given, at which point the participant’s maximum working memory span was recorded.

The Corsi block-tapping test was implemented using The Psychology Experiment Building Language (PEBL) open source software. Custom parameters were used in order to randomize the placement of the blocks on screen. All tests were performed using identical laptop computers in isolated rooms away from disturbance.

Transcranial alternating current stimulation (tACS)

tACS was applied at 6 Hz using Humm (Humm, California). The stimulation electrodes were located over bilateral PFC centered at AF3 and AF4 of the 10-20 electrode coordinate system (Fig 6a). A sinusoidal oscillating current of 750 μA peak amplitude (1,500 μA peak-to-peak amplitude) was delivered to AF3 and AF4 with a 180° phase offset. The tACS group received stimulation for a total duration of 15 minutes, during which they completed the second test battery. Stimulation modeling was performed using SimNIBS to verify electrode positioning and current density at the targeted neuroanatomical regions (Fig 6b).

For the control group, stimulation was delivered with a 30 second ramp up period followed immediately by a 30 second ramp down period and turned off for the remainder of the stimulation session. This was performed in order to appropriately blind participants by producing a sensation of stimulation without eliciting changes to cognitive function. In order to confirm blinding, all participants were asked to rate their perceived effect of tACS on their performance.
Statistical analysis

Differences in performance measures between the tACS and control groups were assessed by repeat measures analysis of covariance (ANCOVA) with pre-stimulation performance and expectation score as covariates and intra-stimulation and post-stimulation performance as dependent measures. This model assesses the difference in intra- and post-stimulation measures after accounting for pre-stimulation measures. The results of this analysis therefore reflect the effect of stimulation and are not affected by the differences in baseline score and expectations between groups. This model is suitable when post-intervention measures are not predictable based on pre-intervention measures, and has been used in assessing cognitive training and performance outcomes.\(^\text{70}\)

Differences in performance between tACS and control groups for individual test batteries were further analyzed with independent samples t-tests. Analysis was performed on both the absolute working memory capacity and the relative change in memory capacity standardized against each participant’s baseline. The effect of expectation bias and the interaction between expectation and group was further assessed using a two-way ANOVA. Cohen’s $d$ was calculated to assess the effect size of tACS. The statistical significance threshold was set as $p < 0.05$. 

Fig 6. a) Electrode positioning of Humm, b) Simulation of current density induced by Humm.
Group variance in working memory performance was verified using Levene’s test for equality of variances. Each group was also verified for similarity in age and gender distribution.

Results

tACS effects on working memory

Repeat measures ANCOVA showed a significant difference in working memory performance between the tACS and control groups (F1,34 = 48.52, p = 6.85x10^-8, ηp2 = 0.60). No significant effect of expectation score was found on performance (F1,34 = 2.62, p = 0.12, ηp2 = 0.076).

Independent samples t-tests were performed to evaluate the differences between the two groups in terms of tACS effects on working memory performance. There was no significant difference in working memory performance between the tACS and control groups at baseline (meancontrol = 5.19, meantACS = 5.03, p = 0.65), nor was any significant difference in variance of working memory performance observed between the two groups (F = 0.44, Sig. = 0.51). There was a significant between group effect of tACS on both intra-stimulation performance (meancontrol = 5.2, meantACS = 6.23, p = 0.004) and post-stimulation performance (meancontrol = 5.09, meantACS = 6.12, p = 0.004). Detailed results of independent samples t-tests are shown in Table 3. This represented a 19.8% greater working memory capacity during stimulation with tACS compared to the control group, and a 20.2% greater working memory capacity following stimulation.

Next, an effect size was calculated based on the mean and standard deviation of the intra-stimulation and post-stimulation performance for both groups using Cohen’s d. A strong effect size was found for the tACS group during stimulation (d = 1.32) and following stimulation (d = 1.07). No effect was found in the control group for either intra-stimulation performance (d = 0.01) or post-stimulation performance (d = 0.10).

Results were then standardized against each participant’s baseline in order to assess the absolute change in working memory capacity. A significant between group effect of tACS was found for both intra-stimulation performance (meancontrol = 0.01, meantACS = 1.20, p < 0.001) and post-stimulation performance (meancontrol = 1.09, meantACS = -0.1, p <
0.001) (Fig 7-9). Measured relative to each participant's baseline, tACS produced a 120x improvement in working memory capacity compared to the control group and this effect was found to persist after stimulation was complete. 94% of participants in the tACS group demonstrated an improvement in performance, whereas only 50% of participants in the control group showed an improvement, regardless of size.

No relationship between expectations and performance

A two-way ANOVA was used to further assess the interaction between group and expectation bias, with expectation rating and group as independent variables, and change in working memory during stimulation as the dependent variable. No significant effect of expectation on working memory performance was observed ($F_{10,20} = 2.02, p = 0.087, \eta^2_p = 0.51$), nor was there any interaction between expectation and group, indicating no significant difference in expectation bias between the groups ($F_{4,20} = 1.94, p = 0.14, \eta^2_p = 0.28$). Working memory performance was higher in the tACS group across all reported expectation scores, however there was no trend or significant effect of expectation on performance.

Confirmation of participant blinding

In order to confirm appropriate blinding, independent samples t-tests were performed on the participant expectation and perceived benefit scores. No significant difference was found between the two groups for either expectations (meancontrol = 5.89, meantACS = 5.75, $p = 0.82$) or perceived benefits (meancontrol = 6.53, meantACS = 6.08, $p = 0.42$), indicating successful blinding.
Fig 7. Effect of tACS on working memory performance during and after stimulation (error bars indicate standard error).

Fig 8. Scatter plot and linear regression displaying distribution of working memory performance for control and tACS groups throughout all test batteries.
Fig 9. Trend in working memory performance throughout test batteries for control group (top) and tACS group (bottom).
A clear positive trend is seen with tACS, persisting after stimulation is complete.
Table 3. Results from independent samples t-tests between control and tACS groups. Performance scores refer to group mean of maximum working memory capacity (WM) in number of items, for each battery (pre-, intra- and post-stimulation). Standard errors are provided in parentheses. Analysis of mean change in working memory capacity from baseline ($\Delta$WM) is provided. Additionally, participant’s pre-stimulation expectation scores and post-stimulation perceived effect (self-reported ratings between 1-10) were compared between groups.

<table>
<thead>
<tr>
<th></th>
<th>Mean - Control</th>
<th>Mean - tACS</th>
<th>Mean Difference</th>
<th>t</th>
<th>p</th>
<th>95% CI Lower</th>
<th>95% CI Upper</th>
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<td>WM Pre-Stim</td>
<td>5.189 (0.259)</td>
<td>5.031 (0.223)</td>
<td>0.158</td>
<td>0.463</td>
<td>0.647</td>
<td>-0.537</td>
<td>0.854</td>
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<td>WM Intra-Stim</td>
<td>5.200 (0.263)</td>
<td>6.233 (0.208)</td>
<td>-1.033</td>
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<td>WM Post-Stim</td>
<td>5.089 (0.221)</td>
<td>6.122 (0.258)</td>
<td>-1.033</td>
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<td>-1.723</td>
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<td>$\Delta$WM Intra-Stim</td>
<td>0.011 (0.165)</td>
<td>1.203 (0.131)</td>
<td>-1.192</td>
<td>-5.648</td>
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<td>$\Delta$WM Post-Stim</td>
<td>-0.100 (0.129)</td>
<td>1.092 (0.173)</td>
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<td>Expectation Score</td>
<td>5.889 (0.447)</td>
<td>5.75 (0.384)</td>
<td>0.139</td>
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<td>0.815</td>
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<td>Perceived Effect</td>
<td>6.528 (0.369)</td>
<td>6.083 (0.401)</td>
<td>0.444</td>
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<td>0.420</td>
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| Std Dev | 0.95 | 0.88 | 1.09 | 1.63 | 1.70 | 7.70  |
| Std Error | 0.22 | 0.21 | 0.26 | 0.38 | 0.40 |

*Table 4.* tACS group - performance and expectations data.
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*Table 5. Control group - performance and expectations data.*
Table 6. Statistical analysis of absolute working memory capacity between control (sham) and tACS (verum) groups, for intra- and post-stimulation conditions.

<table>
<thead>
<tr>
<th>Group</th>
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<th>Std. Deviation</th>
<th>Std. Error Mean</th>
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<table>
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<tr>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>95% Confidence Interval of the Difference</th>
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Table 7. Statistical analysis of change in working memory capacity from baseline between control (sham) and tACS (verum) groups, for intra- and post-stimulation conditions.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
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Table 7. Statistical analysis of change in working memory capacity from baseline between control (sham) and tACS (verum) groups, for intra- and post-stimulation conditions.
Discussion

This trial investigated the effects of frontal theta electrical stimulation on working memory performance, delivered through the Humm headset. The results showed a rapid and significant enhancement of working memory during stimulation, and these benefits continued to be sustained following the completion of stimulation.

The findings reported here indicate a mean improvement in maximum working memory capacity of 19.82% during stimulation. Of the 18 participants in the tACS group, 17 demonstrated an improvement in performance throughout testing, whereas only 9 participants in the control group showed an improvement.

Importantly, the participants’ expectations of the efficacy of stimulation were not found to have an effect on their performance. Additionally, ratings were comparable from pre- to post-stimulation, indicating that many participants could not perceive the effects of stimulation, despite significant improvements in performance. This presents a challenge in which immediate and meaningful feedback must become an integral part of the user experience, in order to drive reinforcing behavior and greater understanding of the efficacy of the device.
Significance of Improving Working Memory

The ability to safely enhance working memory on demand provides a practical tool for improving learning ability and performance in a broad range of applications. Working memory refers to the ability to temporarily hold information in immediate awareness for processing, and is well established as an important predictor of cognitive performance. Working memory is largely responsible for reasoning ability, critical to mathematical cognition and is a stronger predictor for future success in education than IQ. Working memory performance is associated with a variety of cognitive functions that we frequently utilize in everyday life, such as attention, perception and multitasking. Such cognitive functions are known to decline with aging and are attributed to deterioration in prefrontal cortex anatomy and physiology. Noninvasive brain stimulation may improve cognitive function in aging, and may complement lifestyle interventions such as cognitive training and physical exercise. By improving the performance of working memory we anticipate a variety of benefits in everyday life, many of which have been reported extensively by our early customers and which we continue to study and further characterize.

1. ‘Focus easier’ - Working memory capacity is correlated with an increased ability to focus and improved creativity.

Working memory capacity has been found to benefit analytic problem solving by assisting problem solvers to direct and control their focus of attention, resist distraction, and narrow their search within a problem space. Similarly, working memory capacity reflects the ability to apply activation to memory representations, that is to either bring them into focus or maintain them in focus, especially in the face of interference or distraction. Furthermore, individuals with lower working memory capacity have been observed to
experience more interference from task-irrelevant information due to weaker preparatory control prior to stimulus presentation.\textsuperscript{98} In fact, in both laboratory and real-world style assessments, people with lower working memory capacity are seen to suffer mind-wandering more frequently than those with higher working memory capacity.\textsuperscript{99}

Working memory has also been found to benefit creative insight, musical improvisation and original ideation, enabling the individual to maintain attention focused on the primary task and preventing undesirable mind wandering.\textsuperscript{100}

2. ‘Multitask better’ - Working memory is the most important contributor to, and predictor of, multitasking ability.

Working memory plays an important role in multitasking performance, being its best predictor, followed by reasoning, fluid intelligence and attention.\textsuperscript{101,102} In tests of multitasking ability, subjects with higher working memory capacity exhibited better performance than their peers as test difficulty increased.\textsuperscript{103} Multitasking accuracy has been found to be associated with the ability to store information in working memory after the information is no longer present, while multitasking speed is predicted by the ability of an individual to build new relations between elements stored in working memory.\textsuperscript{101} Similarly, task switching ability, as measured by reaction time and accuracy, shows a strong relationship to working memory capacity.\textsuperscript{104}

Working memory capacity is known to confer protective effects against errors during interruptions in cognitively demanding tasks, with significant real-world consequences.\textsuperscript{105,106} Higher working memory capacity was found to mitigate the negative influence of interruptions, multitasking and poor sleep in emergency physicians, leading to fewer clinical and prescribing errors.\textsuperscript{107} Interruptions and multitasking increase cognitive load by placing demands on working memory capacity, requiring individuals to process information unrelated to their primary task. As such, higher working memory capacity
allows information to be maintained and retrieved more effectively following disruption. 107,108

3. ’Remember more of what you read’ - Working memory capacity is associated with an increased ability to successfully encode and retrieve long-term memories.

Improving working memory capacity may have beneficial effects for long-term memory formation, having been found to influence learning ability in specific types of activities. In tests of category learning, an important and common learning strategy where concepts or items must be successfully grouped by their attributes, participants with higher working memory capacity learned rules faster and exhibited greater accuracy.109-111 fMRI and behavioral studies have also demonstrated an important role of working memory maintenance in subsequent long-term memory performance. 112,113 Additionally, working memory capacity is highly correlated with reading comprehension ability, which may aid performance in studying written material.109,114

Higher working memory capacity is also associated with performance in motor learning and may provide advantages in physical skill acquisition, such as in sports and music. Individuals with higher working memory capacity are known to display greater improvements in motor learning than their counterparts.115,116 Similarly, motor learning has been found to improve when instructions are provided in a way that minimizes working memory burden, suggesting a critical role for working memory in the limitation of motor learning ability.117,120

In addition to long-term memory formation, working memory has been found to influence long-term memory recall ability. In tests of long-term memory search and recall, individuals with higher working memory capacity were able to recall more items and with greater speed than individuals with lower working memory capacity.121,122 These findings suggest
that working memory is critical in the search and retrieval of information encoded in long-term memory, and may have important implications for learning ability.\textsuperscript{121,122}

These observations are supported by the findings that similar cortical regions are involved in both working memory and long-term memory, and that stronger theta power observed during working memory maintenance is associated with successful long-term memory encoding. Specifically, long-term memory formation is regulated by the dorsolateral-prefrontal cortex, through its role in the organization of information in working memory.\textsuperscript{113} The same bilateral and dorsolateral prefrontal cortical regions are engaged during the encoding and recognition phases that support both working memory and long-term memory.\textsuperscript{123} Cortical activity during the initial stages of working memory maintenance has been observed to directly contribute to successful long-term memory formation, and this effect is mediated by a network that includes the dorsolateral prefrontal cortex and the hippocampus.\textsuperscript{112} When observed by EEG, stronger theta power is measured initially during the working memory maintenance phase associated with subsequently remembered stimuli, which supports the idea that theta oscillations modulate successful long-term memory encoding.\textsuperscript{124}

4. **Caffeine and other stimulants significantly reduce the quantity and quality of sleep, irrespective of their timing of use.**

The significant detrimental effects of caffeine on sleep are well established.\textsuperscript{125-128} It has been shown that caffeine use in normal subjects induces symptoms mimicking those of clinically diagnosed insomnia.\textsuperscript{125} Caffeine typically prolongs sleep latency, reduces total sleep time and sleep efficiency, and worsens perceived sleep quality.\textsuperscript{126} Caffeine causes rapid eye movement (REM) sleep to shift towards the earlier part of the night and Stages 3 & 4 sleep to shift towards the later part, resulting in increased light and disrupted sleep, with decreased deep restorative sleep.\textsuperscript{125} Slow-wave sleep and EEG slow-wave activity are typically reduced, whereas Stage 1 sleep, wakefulness, and arousals are increased.\textsuperscript{126}
Dosing of caffeine even early in the morning has significant detrimental effects on sleep the subsequent night. A typical 200mg dose of caffeine administered at 7:10 AM has shown, as compared to placebo, a significant decrease in sleep efficiency and total sleep time, all of which are vital for healthy, restorative sleep. Studies consistently show that administration of caffeine results in a significant reduction in EEG spectral power density within slow-wave delta band activity, an area of EEG spectra that is correlated with healthy non-REM deep restorative sleep.
Customer Testing

The focus of the team here at Humm has been to develop a consumer-oriented, simple and elegant device from day one. Other devices within the neuromodulation industry have universally been expensive, bulky, unintuitive and intimidating, with a high barrier to use. It was clear to us that any device we make has to address the issues of cost, approachability, and ease of use. Through early prototyping of various form factors and user experiences tACS, we settled on the central ethos of Humm to be Simple, Cheap, and Elegant. The evolution of this process, the steps we have taken, and the invaluable information we have learned is detailed below.

Humm as a product is a beautifully elegant, cheap, and simple to use patch constructed from fabrics, foams, gels and electronics. But this has not always been the case. To ensure we built a device that fits this description, and was as user-friendly as possible, we have gone through a journey of iterating prototypes, and consistently testing these prototypes with our valuable pre-order customers.

Internal testing

Very early on, to ensure Humm was focused on making the best product possible, we narrowed down on and formalized the four key features the patch was to perform. We then iterated on prototypes to improve upon the design based on assessing the success of these features.

Features

1. Successfully adhere to the user’s forehead in 95% of the population, during a single 15 minute session.
2. Deliver a validated neurostimulation protocol to the prefrontal cortex.
3. Ensure neurostimulation is provided in the most comfortable manner as possible.
4. Minimize complexity of operation, with a maximum of only three steps from package to forehead without needing to read instructions.
Prototypes

Over two years of development we worked to iterate on preliminary designs, incrementally improving the comfort and durability of the device. The below images show the evolution of the form factor from early to final prototypes.
Customer feedback

Gathering, collating, and acting on user feedback has been vital for Humm in guiding the development of prototypes. We engaged 121 customers in our Early Access Program over several months for this purpose.

Age demographics

As shown in Fig 10, the largest subgroup of testers were within the 20-30 year old age bracket. The initial testing group demographics favored this age bracket due to marketing focusing more on a younger audience, however, as we continued testing and gathering feedback, we noticed significantly higher user retention and NPS score in the 41-70 age bracket. We hypothesized causative factors for this phenomenon specific to this age group as:

1. Greater self-awareness of own learning ability and style
2. More focused use cases on activities that stressed working memory
3. Lower reliance on stimulants (eg. coffee, energy drinks or prescription stimulants)

Fig 10. Age demographics.
Use cases

The activity during which the patch was used played a significant role in the end user experience. The more that the activity stressed working memory, the better the subjectively reported user experience. The use cases for which we received the best feedback were:

1. Studying
2. Reading
3. Learning a language
4. Writing
5. Coding

Notable use cases in which there was limited positive feedback was in those cases where working memory was not heavily taxed, and where there was an overall low cognitive load. Some examples of these include use while watching football, cooking, or weight lifting.

Fig 11. Use cases.
Occupation demographics

Fig 12 shows the distribution of occupations within our user test groups. The majority of users fell within a high socio-economic bracket and either seeking or having obtained higher education. As with most new innovative technology, our early adopters tended to have a higher level of disposable income.

Medical professionals within our test groups were medical doctors, physiotherapists or psychologists. Data scientists and biological scientists were grouped together. Business managers ranged from mid-level managers to executives. Of note, approximately half of the business managers were working in sales or business development. Finance professionals were primarily working in venture capital, likely explained by our location in the San Francisco Bay Area.
Why a patch?

Consumer neurostimulation devices have predominantly been expensive, bulky, unintuitive and intimidating. Our goal has been to make existing and proven neurotechnology simple and consumer-friendly in order to remove the existing barriers to entry. The cheap, simple and elegant patch form factor achieves four main goals:

1. **Resetting expectations**
   Customers often have elevated expectations that an expensive device will provide instant and inordinate benefits, rather than more measured advantages that will help the user achieve their goals and potential faster. Reducing cost better aligns expectations with the demonstrated benefits of the technology.

2. **Increasing convenience**
   We have made countless novel design decisions to reduce the mental load on the user and minimize the chance of frustration and confusion, including:
   * Eliminating unnecessary actions (e.g. charging batteries, replacing hydrogels or foams, untangling wires)
   * Using familiar cues (application similar to a BAND-AID™ or sticker)
   * Creating a seamless and efficient customer experience all the way through from ordering, first-time use, replenishing and ongoing usage

3. **Ensuring lifestyle fit**
   It is easier to attempt fitting into customers current behavioural patterns than it is attempting to change them. In this case, a patch is easily able to be placed into a user’s bag and carried around with them, as opposed to having to create a dedicated time-place opportunity to use a bulkier, fixed device.

4. **Increasing adoption and education**
   The purchase price of most neurotechnology devices presents a significant barrier of entry for a new and unfamiliar technology. We are guided by the analogy of offering a $5 cup of coffee rather than a $500 espresso machine to customers who have never tried coffee. This allows more people to try and experience a novel technology that would otherwise be out of reach, and provides an opportunity to build awareness of neurotechnology and its significant and potentially wide-reaching benefits.
Testimonials

“This is my third use, and so far it consistently seems easier to make myself focus on something after using the patch. Recovering from distractions also seems easier.”
Mathematician, age 40-50

“I felt upbeat and focused. Experienced moderate phosphenes.”
Business Owner, age 40-50

“My sudoku time was measurably better than usual.”
Business Development Manager, age 40-50

“I did not find myself going back to re-read various sections as often as I have in the past.”
Software Engineer, age 40-50

“I kept very focused on the task at hand. Even after finishing, my mind is staying focused and not wandering.”
Librarian, age 50-60

“Quantitatively, the flashcard software I use to study tracks my productivity. I was able to boost my daily performance and increase my flashcard output from 101 cards to 136.”
Medical student, age 20-30

“I was able to keep my spot while reading and didn’t have to go back several times to reread the same material over and over again.”
Software Engineering student, age 20-30

“Worked at a faster pace and had more clarity in my thoughts.”
Lawyer, age 20-30
Conclusion

“The world has never moved as fast as it is today … but never again will it move this slow”.

The pace of technological innovation, the amount of information we must cope with each day and the rate at which we must learn new things in order to stay relevant in a changing world - all these things are constantly accelerating. While it’s certainly true that our brains are naturally able to continue changing and learning even late in life, it’s also well known that many measures of cognitive ability tend to decline from our twenties as we grow older. This is just one of those facts that we’ve all internalized and dubbed ‘healthy aging’, like wrinkles or grey hair. But for a huge proportion of people this effect increasingly becomes a trap as we age, a reason that we can’t keep up with change nor continue to challenge ourselves to learn new things. And so, we increasingly lose the curiosity and drive for learning that brings so much joy and personal growth earlier in life.

As our ability to extend human lifespan improves, the world’s population ages at an increasingly unprecedented rate. In 2018, for the first time in history, persons aged 65 or above outnumbered children under five years of age globally, and the number of people aged 60 and over is forecast to double from 1 billion in 2019 to 2 billion by 2050. This has massive societal implications, not least of all a large impact on the global economy, but perhaps most poignantly it means an increasingly large number of people may struggle to feel relevant and challenged in a rapidly changing world.

In response, aging Baby Boomers and Generation Xers have driven an explosion in activity in what is now multi-billion dollar consumer brain health market, despite many brain training services and cognitive supplements being largely unvalidated and with limited evidence of any return on investment on the billions spent. At the same time, young college students and knowledge workers are driving billions into the cognitive enhancement market, seeking to boost their performance in increasingly fluid and demanding work environments (through behavioral strategies, energy drinks or the abuse of prescription medications). Combining these trends across adult populations, there’s a strong case that improving cognitive performance is a large and growing market in need of truly effective and safe technology.
Transcranial electrical stimulation has been studied for decades as a method to support and enhance cognition, and has received FDA clearance for the treatment of particular neurological and psychiatric disorders. Humm has developed a consumer-grade wearable patch that gently stimulates the brain’s natural rhythms to strengthen working memory, using transcranial alternating current stimulation (tACS) to target specific patterns of neural activity in the prefrontal cortex. This technology is based on tens of thousands of participant trials, with a strong track record of safety and no serious adverse effects. Humm has reinvented the form factor from a bulky headset to a disposable patch, driving down the cost per use to that of a cup of coffee. In initial studies, Humm has demonstrated that 15 minutes of stimulation produces a 20% improvement in working memory, lasting at least 90 minutes and showing a demonstrable positive impact on people’s cognitive ability. Future products will also include cognitive assessments to track improvement over time and enable personalized stimulation.

We believe that Humm’s innovation in form factor, design and cost - while maintaining quality and safety on par with clinical devices - is the key to minimizing barriers to adoption and democratizing access to this validated cognitive improvement strategy, especially for young and old knowledge workers in increasingly complex work environments. By minimizing barriers to adoption, Humm’s wearable patch will significantly increase the fraction of the world’s population that can benefit from accelerated learning, for growth, happiness and health. Our technology provides an effective and safe alternative to the billions being spent today on ineffective solutions. Humm’s technology will also dramatically increase the speed and lower the cost for scientists seeking to investigate the use of transcranial stimulation technology in the treatment of neurological disorders such as ADHD and Alzheimer’s disease.

Building upon generations of exploration into the inner workings of the brain, we hope to contribute to the next step in our shared journey to understand the most complex system in nature. By driving education and increasing access to neurotechnology, we aim to build demand and curiosity for this technology and its potential benefits and applications. We envision a world where advances in neuroscience and technology allow us to improve the health and performance of our brains, opening new possibilities for how we experience and enjoy our lives.

Let’s start building that world today.
Disclaimer

These statements have not been evaluated by the Food and Drug Administration. This product is not intended to treat, cure, or diagnose any diseases or medical conditions.

Please note that Humm Patches are intended solely for use by healthy adults only for purposes of supporting working memory. We hope to expand the use of this technology to help people with specific medical conditions in the future, but we have not yet gathered the clinical data necessary to advise on the safety or efficacy of the use of Humm Patches for any such purposes.

Humm Patches are not recommended for use by individuals who are under the age of 18; have implanted metal or electronic medical devices in the head or neck; have a cardiac pacemaker or implantable cardioverter-defibrillator; have a history of seizures; are pregnant; or have undergone any brain surgery. Consult your physician if you believe any of these may apply to you, or if you have any other concerns.
References


