A Experiment Material

Recruitment Material. Fig. 1 shows the study advertisement, distributed as flyers and posters across the university campus and announced during lectures.

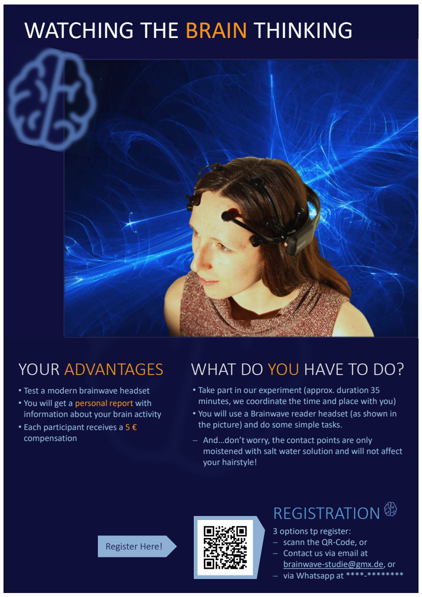

Figure 1: Flyer used for participant recruitment

Experiment Instruments. The experiment starts with the experimenter providing the participant with a consent form. After giving consent, the participant is shown a sequence of images (printed in paper) and told to choose one. He/She is also assigned another picture and told to remember it. Next, the participant seats in front of a PC screen, receives a paper form to write answers in the subsequent steps, and the experimenter fits the EEG headset to him/her. From that moment on, the experimenter tells the participant to follow the instructions in the screen, summarized in Tables 1, 2, and 3. Once the brainwave collection is finished, the participant is asked to fill a paper survey to evaluate the perceived usability of a brainwave authentication system based on the performed tasks and gather demographic data. The survey questionnaire is detailed in Table 4 and Table 5 contains the codebook used to analyse free text questions. After the survey, once the experiment is finished, the participants get their compensation and have the chance to ask questions. They will be contacted in the following days to receive a personal report on their brain activity during the experiment.

Personal Report. The report explains the different type of brainwaves a person has in different states (e.g., when attentive or idling), describing where they originate and which electrodes capture them. It also provides graphs showing the mental state of the participant during the experiment as derived from his/her brain activity. The graphs show: stress

Introduction
Welcome to our Brainwave study. The study will take approximately 30 minutes. Please take a seat now and try to move as little as possible during the tasks. You can move during breaks. When you're ready to start, please press the space bar. You can use the space bar to navigate to the next step in the entire process. Let's begin.
Baseline
Now keep your eyes open for 20 seconds and relax. If possible, try not to blink during the 20 seconds.
Now relax with your eyes closed for 20 seconds. Keep your eyes closed until you hear an acoustic signal.
Now open your eyes and press the space bar to start.
P300:Selected and P300:Assigned
You will see the following task a total of six times during the experiment. You will see a series of pictures during the task. Press the space bar to start the task.
Now remember the picture you selected (were assigned) at the beginning of the experiment. Your task in the following is to count how often exactly this picture occurs. Press the space bar to start.
[Images]
How often have you recognized your picture? Write the number in the space provided on your paper.
N400:Words
You will now watch a video. After the video, you will be asked to note three terms you associate with the video. Press the space bar to start the video now.
The video is about to start. Watch carefully.
[Video]
Please write down three terms you associate with the video in the space provided on your paper. Press the space bar to continue.
You will now see a series of words. Read carefully.Press the space bar to start the series of words.
Subliminal Video
You will now watch another video. Watch carefully. Press the space bar to continue.
[Video]
N400:Sentences
Next you will be shown individual words. These result in sentences. Read carefully and try to visualize the sentences. Press the space bar to continue.
[Sentences]
N400:Faces
You will now see some more pictures. Watch carefully. Press the space bar to start.
[Face Images]
End of Experiment
Thank you very much for participating in our experiment! Please contact your experimenter now. She will conduct a small final survey with you.
After-tasks
Thank you, you have completed [Task i] out of [N] tasks.

Table 1: Brainwave collection experiment instructions.

Related	Car, Track, Road, Highway, Vehicle, Speed, Steering Wheel, Toll, Expressway, Sports car, Automobile, Driver
Unrelated	Apple, Biology, Moon, Circle, Kitchen, Hunger, Opera, Mushroom, Hare, Price, Hotel, Ladder, Selection, Hairstyle, Studies, Chalk, Producer

Table 2: Words used in the N400:Words Authentication Task, related and unrelated to a video showing driving cars.

Sentences	**Priming (Probing) Ends**
I drink coffee with milk and	sugar(socks)
Ted smiled and bit his bottom	lip(rainbow)
The prison ward walked along the	row(moon)
A horse has thrown a	shoe(plane)
Steve sat down to eat his	lunch(car)
He put the fork on the	table (door)

Table 3: Sentences used in the N400:Sentences Task.

level, interest level, engagement level, relaxation level, focus level, and excitement level. Fig. 2 shows a partial example of the graphs included in the personal report.

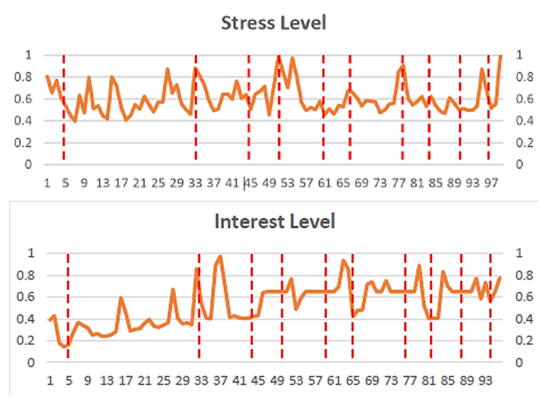

Figure 2: Snapshot of the graphs for "Stress Level" and "Interest Level" (measured every 10 seconds) provided in the personal brainwaves report given to participants after the study. The vertical bars signal task changes.

B Literature Review

Table 8 summarizes the literature on consumer-grade EEG authentication. Descriptions of the reported performance metrics [17] and signal processing techniques can be found in Table 7.

Introduction
We want to build an authentication system based on brainwaves. In order to use such a system, you would have to watch one task out of the set of tasks in the experiment once a day. This step would replace all passwords for all applications you are currently entering. Please score the tasks with regard to their usage in a brainwave authentication system.

Perceived Usability of the Authentication Tasks
Please score the tasks based on three criteria. (1=Strongly Agree to 5=Strongly Disagree)
Q1. The task was boring
Q2. The task required a lot of attention
Q3. I could imagine to perform this task on a daily basis at a PC for authenticating
Q4. Please sort the tasks depending on how enjoyable they were (1=Most Enjoyable, 5=Least Enjoyable)

Perceived Usability of the Device
Q5. I could imagine to put the headset on myself after a short introduction (5=Strongly Agree, 1=Strongly Disagree)
Q6. My experience with the headset was very positive (5=Strongly Agree, 1=Strongly Disagree)

Acceptance
Q7. Do you envision any problems with an authentication system using these techniques?
Q8. Do you have any suggestion for designing an authentication system based on these techniques?

Demographics and Personal Information
Q9. Please indicate your gender. (Options: Male, Female, Other)
Q10. Please indicate your age. (Options: 18-24, 25-31, 32-38, 39-45, 46-52, 53-59, 60 and older)
Q11. Which hand is your dominant hand? (Options: Left, Right)
Q12. I felt rather stressed out during the last week. (5=Strongly Agree, 1=Strongly Disagree)
Q13. I feel tired today. (5=Strongly Agree, 1=Strongly Disagree)
Q14. Did you drink alcohol yesterday? (Options: Yes, No)
Q15. Did you consume caffeine during the last 12 hours? (Options: Yes, No)

Table 4: Usability and Demographic Questions

Category	**Codes**	**Definitions**	**Examples**
Device (n=16)	Design (1%)	Participants report problems in the EEG headset design	"The headsets would need to be smaller, so that it would be practical to take it anywhere"
	Setup (5%)	Participants report problems with the EEG headset setup	"It is too complicated to put on the headset self-employed"
	Cost (2%)	Participants identify the price of the EEG headset as a problem for adoption	"Procurement to expensive"
	Technical Problems (12%)	Participants report envisioned technical problems with the EEG headset operation	"The electrodes are not functioning properly, the system is very sensitive to movements"
Brainwaves (n=21)	Stability (20%)	Participants report concerns with the stability of brainwaves with external (e.g., noise) and internal conditions (e.g., mental states like being tired or under stress)	"Under stress brainwaves are maybe different?"
	Uniqueness (8%)	Participants report concerns with the uniqueness of their brainwaves	"I think it is much harder to get evidence for the uniqueness of individual brainwaves for unambiguous identification than with fingerprint genes"
System (n=37)	Performance (9%)	Participants report system performance, in terms of time to authenticate, as a problem in brainwave based authentication systems	"It takes too long to perform this every day"
	Usability (16%)	Participants report usability problems -other than time performance- of the overall authentication system.	"An authentication system using sentences could be problematic for some people, like for example kids"
	Security & Privacy (13%)	Participants report problems related to the security and privacy aspects of a brainwave authentication system	"With improved and advanced technology: contactless brainwave reading maybe possible at some point and then technical imitation"
	Deployment (6%)	Participants identify problems that arise when the system is deployed in real-life scenarios	"The results of the recording would need to be imported into a new single-sign-on system which also is not straightforward."
	Technical Problems (4%)	Participants report envisioned technical problems in the overall brainwave-based authentication system	"Problems during analysis"

Table 5: Categories and codes used to code free text answers on envisioned problems of brainwave-based authentication. Percentages in parentheses indicate the number of times a code was used.

Category	Codes	Definitions	Examples
Device (n=7)	Design (13%)	Participants suggest concrete changes in the EEG reader design, e.g., to modify its shape	"As a hat"
	Simplicity (5%)	Participants point at the general need to simplify the EEG recording process, without giving concrete suggestions on how to achieve it	"Simplify the headset"
Protocol (n=15)	Design (31%)	Participants suggest modifications to the authentication tasks, or point at features in the tested tasks considered desirable that should be included in a brainwave authentication system	"I would be interested in authentication using music or tones"
	Enjoyability (7%)	Participants report identify as positive that the authentication tasks are pleasant	"I like the idea with incongruent sentences. Generally, I think that it is important to include something funny or encouraging to avoid boredom"
System (n=16)	Performance (21%)	Participants report that a brainwave based authentication system should have a good performance in terms of time to authenticate	"The duration of the authentication has to be kept as short as possible."
	Deployment (7%)	Participants report potential applications of brainwave-based authentication, or identify required improvements/adaptations of the system when deployed in real-life scenarios	"For securing the entry to buildings"
	Usability (13%)	Participants suggest to improve usability aspects -other than time performance- of the overall authentication system	"Less effort for an integration into everyday life" "

Table 6: Categories and codes used to code free text answers on suggestions to improve brainwave-based authentication. Percentages in parentheses indicate the number of times a code was used.

Metrics	
ACC	Accuracy
CRR	Correct Recognition Rate
EER, HTER	Equal Error Rate, Half Total Error Rate
FRR, TPR	False Rejection Rate, True Positive Rate
GAR	Genuine Authentication Rate
Signal Processing	
AR	AutoRegressive model
FIR	Finite Impulse Response filter
FFT	Fast Fourier Transformation
IHLC	Interhemispheric Channel Linear Complexity
IHPD	Interhemisphere Power Difference
PCA	Principal Component Analysis
PSD, PS	Power Spectrum Density, Power Spectrum

Table 7: Performance metrics and processing techniques used in the EEG Authentication literature

	Data Acquisition: Headset	Task	#Ch	Bands	Data Processing: Pre-processing	Features	Alg.	Evaluation: #Sbjs.	#S	Performance
Miyamoto et al., 2009 [9]	n.a.	Resting (EC)	1	α	Spectral analysis	Spectral variance, non-dominant power spectrum	Similarity	23	1	GAR:79%
Nakanishi et al., 2009 [12]	n.a.	Resting (EC)	1	α	Spectral analysis	Same as in [9], convexity of spectral distribution	Similarity	23	1	EER:11%
Ashby et al., 2011 [2]	Emotiv EPOC	Resting (EC), Motor + non-motor imaginary	14	α, β, γ, δ, θ	Elliptic high-pass filter	AR, PSD, PS, IHPD, IHLC	one-vs.-all SVM	5	1	ACC: 100%
Nakanishi et al., 2011 [11]	n.a.	Resting, simulated driving	1	α, β	Spectral analysis	FFT, mean PS, mean PS difference between tasks	Similarity	10	10	EER: 24%
Svogor & Kisasondi, 2012 [18]	NeuroSky Mind-Wave	Relaxation, Concentration	1	α, β	n.a.	MindWave metrics for relax and focus	Similarity	6	1	n.a.
Klonovs et al., 2013 [7]	Emotiv EPOC	Visual stimuli	4	α, β, γ, θ	Butterworth bandpass filter	ICA, PSD, Wavelet Analysis, zero-crossing rate	Similarity	n.a.	n.a.	n.a.
Chuang et al., 2013 [5]	NeuroSky Mind-Set	Resting (EC), motor/non-motor imaginary, auditive/visual stimuli	1	α, β	Extract α, β bands	PS, FT, 5-second recording windows, signal fusion, signal similarity	Similarity	15	2	HTER: 1.1%-43.3%
Mohan-chandra, 2013 [10]	Emotiv EPOC	Meditation, non-motor imaginary (math task)	14	α, β, γ	Extract α, β, γ bands	PS, PCA (only signals with >85% of signal variance), PSD, FT	Similarity	n.a.	n.a.	n.a.
Johnson et al., 2014 [6]	NeuroSky Mind-Set	Same as in [5]	1	α, β	Extract α, β bands	Same as in [5]	Similarity	18	n.a.	HTER: 1%
Nakanishi & Yoshikawa, 2015 [15]	n.a.	Route tracing, simulated car-driving	1	α, β	Spectral analysis	FFT, spectra normalization, PCA	one-vs-one SVM	30	10	EER: 22%-24%
Sohankar et al., 2015 [16]	NeuroSky Mind-Wave	Resting	1	α	n.a.	FFT	Naïve Bayes	10	1	ACC: 95%
Chuang & Chuang, 2016 [4]	NeuroSky Mind-Wave	Visual stimuli, mental task	1	α, β, γ, δ, θ	n.a.	PS, Similarity of PS, Time windows	Similarity	10	1	FRR: 27.8%
Abo-Zahhad et al., 2016 [1]	NeuroSky Mind-Wave	Eye blinking, resting (EC), visual stimuli	1	α, β, γ, δ, θ	Elliptical band-pass filter	Eye blinking signal, AR, Visually Evoked Potentials	Discriminant Analy-sis	31	1	EER: 0.89%
Bashar et al., 2016 [3]	Emotiv IN-SIGHT	Resting (EC)	5	α, β, γ, δ, θ	Band-pass FIR filter	Multiscale shape descriptor, Wavelet Packet Decomposition	Multiclass SVM	9	n.a.	TPR: 94.44%
Kavitha et al., 2017 [19]	Emotiv EPOC+	Self-related visual stimuli	14	α, β, γ, *theta*	Bandpass Filter (0.5-45 Hz)	FFT, IHPD	Similarity	4	2	FAR: 12.5%, FRR: 12.5%
Maruoka et al., 2017 [8]	Emotiv EPOC+	Auditory stimuli (ultrasound)	2	α, β	n.a.	FFT with Hamming Window	Similarity	5	1	n.a.
Nakanishi et al., 2017 [13]	Emotiv EPOC+	Auditory stimuli (ultrasound)	14	α, β	n.a.	FFT with Hamming Window, PCA (3 best features)	one-vs-all SVM	10	10	EER: 4.4%-26.2%
Nakanishi et al., 2019 [14]	Emotiv EPOC+	Invisible visual stimuli	14	α, β, γ	ERP Extraction	PS differences for varied intensity stimuli	Similarity	20	10	EER: 23%

Table 8: Chronological summary of studies on brainwave authentication using consumer-grade EEG headsets.
Legend: #Ch = number of channels, **Alg.** =Algorithm, **#Sbjs.** = number of subjects, **#S** = number of sessions, **n.a.** = not available

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