Can Intentional Binding Travel Through Time?

MSc Psychology Dissertation

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Author's Notes

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Abstract

As humans learn through experience, we develop a Sense of Agency (SoA), which can be measured by the intentional binding (IB) effect—the perceived temporal compression between an intended action and its outcome. This study explores whether the IB effect increases with learning. Participants were trained to associate their actions with the production of a tone, and a control condition was used to determine if the learned information influenced the IB effect in experimental tasks. The results demonstrated the IB effect in active conditions for the 900 ms training group. However, learning for the 300 ms group was too early to produce a significant IB effect for tasks with a 300 ms delay. We conclude that learning with a 900 ms interval more effectively strengthens the IB effect, particularly for 600 ms and 900 ms tasks. Additionally, the study investigated the potential influence of Attention Deficit Hyperactivity Disorder (ADHD) symptomology on learning and time perception, predicting that ADHD symptoms might impair time estimation and learning. In general, the IB effect seems to be negatively correlated with ADHD traits.

***Keywords**: Intentional Binding, Sense of Agency, Temporal Perception, Learning and Adaptation, Human-Computer Interaction, Focus of Attention, Attention Deficit Hyperactivity Disorder (ADHD), Interval Estimation Method*

Introduction: Learning Agency in Humans

Humans learn to have agency in the world. Infants have little control over their own bodies, but as they develop intentional behaviours, they learn to have a feeling of control over themselves and thus the external world (Haggard. P, 2017), cultivating a Sense of Agency (SoA). The SoA is primarily important for humans to understand that *they* are the cause of an event outside themselves, gain an understanding that "*I did this*" rather than an external cause, cultivate a motivation to transform the world outside them through intentional actions and thereby experience the transformation (Haggard. P, 2017). Current scientific literature asserts the SoA can be measured by proxy by a phenomenon known as the *Intentional Binding Effect* (Haggard. P, 2002) in which agents perceive their actions as marginally temporally closer to the external event if they believe they were the cause, warping one's perception of time, and binding together action-and-outcome in the world.

Albeit humans tend to over-estimate what they can and cannot control, (Wegner. D. M, 2002) which makes it especially intriguing to modern science, as not only does SoA produce illusions of control (particularly in certain psychiatric disorders) but also opens the door to understanding how we can manifest a feeling of control and learn to associate agentic control over extraordinary circumstances; For instance, this forms foundational research in brain-machine interfaces (BMIs) and the acquisition and control of motor-skills in neuroprosthetics by thought alone (Koralek, A. C.,et al (2012).

In the same vein, there is emerging evidence that internal and external psychological factors can diminish or distort one's feeling of control; Research has uncovered that the IB effect is modulated by states of arousal; such as fear and anger (Haggard, P., 2019), negative affect (Rigoni D, 2015), social coercion (Caspar EA, 2018), old age (Cavazzana, P. S., 2017), psycho motor-control conditions such as anarchic hand-syndromes (Della Sala S, et al, 1991) and Parkinson's disease (Saito et al., 2017), psychiatric conditions such as schizophrenia and obsessive compulsive disorder (Ford, J. M., 2014, Gentsch, et al, 2012), and personality traits such as narcissism (Dimaggio, G., 2015) and borderline personality disorder

(Möller, T. J., 2020). However, discussing these relevant extraneous variables as possible influences on this experiment should be considered, but discussion is beyond the scope of this thesis.

To summarise, prior literature emphasises that IB is malleable, indicating that humans' SoA can similarly be changed. Modulating IB through learning could have broader implications for enhancing human's feeling of agency, contributing to high levels of self-mastery and promoting psychological wellbeing.

Reviewing the literature on the IB paradigm, this review is structured as follows:

The first section overviews how learning in human-computer interactions have enhanced the sense of agency so far and gives reason for designing our experiment on a computer.

The second section reviews the current literature on identifying the precise time-window for optimizing intentional binding and the methodologies employed to achieve this.

The third section explores how physical learning and refinement can enhance one's sense of agency.

The fourth section considered why time-perception is warped in the IB effect and the role of focus of attention in explaining possible variations in learning and IB effect in this experiment.

Literature Review

Learning Agency in Human-Computer Interactions

The SoA is changed by daily life as humans learn what they can control. For instance, a cyclist experiences instrumental control as she peddles harder up a hill; she experiences acceleration as sensory feedback, thus increasing her sense of agency (Haggard, P. 2017). Likewise, a gamer moving left on a joystick expects their avatar to move left on screen, and they know that *"I did that",* but if their actions are not congruent with the avatars, the subject will interpret "*the system did that"* there is something wrong with the technology. Cornelio, P et al. (2022) argues this is how agency is something that is, and can continue to be, learned through human-computer interactions (HCI) and states that if the technology is sophisticated enough to produce a smooth interaction between action and sensory feedback, has controlled movement, and has highly predictable outcomes, this will generate the IB effect.

But stimuli also need to exist *at the right time*; To find the precise time measurement to induce IB is crucial data for understanding when the "*I did this*" feeling emerges and how enhancement of the SoA is feasible. To date, research on enhancing SoA in human-computer interactions has predominantly focused on the precision of time intervals required to trigger the IB effect; The technology designed to optimize IB must be fully congruent with a subject's thoughts, actions and immersive enough to provide sensory feedback information.

Wegner & Wheatley (1999) elucidates this by identifying three critical variables for the manifestation of the feeling "*I did this*":

1.) There must be a *brief delay* between action and event, ensuring that the thought precedes the action.

2.) *Consistency and exclusivity* are essential—how consistently the event follows the action and how often the event occurs without the action.

3.) The *action must predominantly cause the event,* rather than any other cause, thus creating the feeling of control.

4.)

The next section addresses challenges in measuring intentional binding (IB) in human-computer interactions and gives reason for this study's design.

Experimental Methods and Cofounding Factors

Studies so far have attempted to find a temporal window for IB in human-computer interactions: One study by Ruess, M, et al (2017) investigated this at various delays, including 200 ms, 250 ms, and 300 ms. Participants were instructed to press a key, which triggered a tone after a range of delays and used the Libet Clock method (LC) (Libet et al., 1983), to determine time perception in voluntary and involuntary conditions. The results demonstrated significant IB effects for all tested delays, with the optimum presence of this effect within the 200-300 ms range. Also, if the time-delay occurs too early, at 150ms, this will not induce IB. This study corroborates the idea that IB can usually be observed at delays between 200 and 500 milliseconds, which has been the predominant timeframe in the literature to date, but the IB effect starts to decrease beyond 400ms.

Paradoxically, the IB effect was shown in results to recover when the delay extended to 850ms. An answer to this could be that IB is at least in part caused by an *inferential mechanism* designed to make *retrodictions* (Donapati, R., (2024). This suggests that the IB effect is not limited to a specific temporal peak but is influenced by multiple underlying components, indicating that it can theoretically be induced through various mechanisms.

Considering this, one rationale for designing this experiment using a computer is based on the evidence that humans effectively attune to sensory stimulus from a computer (Buetler et al, 2022). Additionally, we have structured tasks using the timeframes from previous IB experiments.

However, it is important to note that human's sensitivity and sensory-processing in human-computer interactions is to an extent subjective. Research has identified stimulus intensity as a confounding factor in perceiving temporal-compression, making the precise time window for the IB effect uncertain, and when the IB effect occurs maybe attributed to methodologies and cognitive processes. For instance, psychophysical experiments attempting to gauge perceptual thresholds in the IB effect, by correlating sensory stimulus intensity with subject responses (Donapati. R, 2024).

One experiment employing the *method of constant stimulus* (in which participants are exposed to a randomized sequence of stimuli of varying intensities, spanning from subthreshold to suprathreshold) found the IB effect at 600ms but not at 250ms when comparing auditory and visual conditions with active or passive keypresses (Nolden et al., 2012). This outcome deviates from the consensus on IB, showing that the IB effect happens at longer durations rather than shorter ones. Ruess et al. (2017) and Nolden et al. (2012) demonstrate that multiple factors contribute to the IB effect, influenced by varying sensitivities and sensory processing. Sensory-stimulus intensity and receptivity should be accounted for, as unaddressed variations could introduce biases through selective attention and perception.

Additionally, using human-computer interaction to measure IB may infer a SoA indirectly, which might not accurately reflect the participant's experience. Time-compression can occur without a clear SoA, so interpreting IB as a direct measure of intentional action requires caution.

This line of thought was articulated in a study by Gaiqing Kong, et al (2024) investigating if the IB effect is genuinely intentional; In the first experiment, participants were tasked with estimating the temporal delay in three conditions: an active movement (a voluntary keypress), a passive movement (experimenter-pressed key) and an external sensory event (tone). The trials had varied intervals: 150ms, 450ms and 750ms and used the *interval estimation method* to judge time-perception post-hoc.

The second experiment was parallel to the first, except instead of estimating the time delay between a trigger and a tone, the participants saw a visual stimulus (in this case a light visible at different distances using VR) and reported their experience on a gamepad slider in VR. The results showed that temporal binding was most effective at the 750 ms interval, followed by the 450 ms interval, and no effect observed at the 150 ms interval. This pattern suggests that temporal-binding becomes more pronounced as the delay between events increases. The results also showed that there was no substantial evidence for intentional binding, instead there was evidence of non-intentional temporal-binding and suggesting that temporal-binding does not require voluntary action and instead can arise from sensory integration, expectations and predictability.

In contrast to Nolden et al. (2012), Kong et al. (2024) found no evidence that temporal binding is driven by goal-directed behaviour. The study also did not replicate the bell-curve IB pattern identified by Ruess et al. (2017), suggesting that IB is not confined to a specific time window and that temporal compression can occur at various intervals. Additionally, "intent to act" is not required for temporal compression, which may result from *passive learning* and the mind's adaptation to new information and patterns.

The next section will analyse empirical evidence to infer that *active learning* enhances the intentional binding effect and provide further rationale for this experiment.

Learning Expertise and Agency

The discussion so far indicates that the precise temporal window for inducing intentional binding remains indeterminate due to numerous confounding variables, especially in the context of human-computer interactions. It is plausible that a definitive temporal window may be non-existent.

Nonetheless, it seems learning—whether passive or intentional—modifies time-perception. For instance, there is empirical evidence that motor-skill acquisition, such as practicing a musical instrument or mastering surgical techniques, strengthens the connections between actions and their outcomes, thereby honing motor-skills and enhancing the IB effect. A study by Pansardi, O., et al. (2020), illustrates this by measuring the IB effect in expert pianists:

In this experiment, 28 expert pianists and 28 matched non-musicians were compared. Participants reported the perceived interval between pressing a button and hearing a tone, a random tone, and the action alone. Using a variant of the Libet Clock Method (Libet, 1983), subjects observed a moving clock hand and used it to measure their perception of the time between stimuli. Results showed expert pianists had significantly greater precision and a stronger IB effect than non-musicians. There was no significant difference in the pianists' responses to piano notes versus electronic sounds, suggesting their auditory skills generalize beyond piano playing.

This study suggests that musical expertise positively impacts one's feeling of being in control, likely due to the continuous exposure to action-event sequences and the learning of associative links (Pansardi, O., et al., 2020). Mastering a motor skill, which necessitates active learning through self-initiated actions, motivation, and sensitivity to response signals, hypothetically should result in an enhanced SoA when individuals are assessed on their mastery and control over their actions and outcomes. For example, Virtual reality (VR) in surgical training simulates real-life scenarios and adjusts task difficulty based on performance, enhancing hand-eye coordination (Harrison et al., 2017). Harrison et al. (2017) compared VR to standard video demonstrations for teaching the ACORN Surgical Hand Preparation (SHP) technique. While no significant differences were found, VR did show a trend toward better skill acquisition and retention.

This evidence suggests that actively learning and refining a physical technique, through repeated practice and building action-outcome understanding, increases sensitivity to environmental ques and improves predictive processing in the supplementary motor cortex area of the brain (Buetler et al. 2022, Seghezzi, Zapparoli, 2020). Therefore, this should increase the IB effect.

A study by Silvia Seghezzi et al (2023) showed that learning when to act in experiments boosts a subject's SoA by increasing sensitivity to their mistakes, listening for sensory feedback information, and continuously adjusting behaviours to reach their goal (Seghezzi et al., 2023). This conclusion is also supported by a study by Majchrowicz et al. (2020), which shows a greater IB effect when subjects learn from their mistakes, as failures provide more information than successes.

Given these findings, further investigation into how learning modulates intentional binding is warranted, motivating our current experiment.

This experimental design is unlike Seghezzi et al. (2023) and Majchrowicz et al. (2020) that have investigated the role of learning in the intentional binding effect before, as our design excludes error feedback, preventing participants from learning from their mistakes. Instead, this experiment aims to determine if a brief introductory learning procedure provides enough exposure for participants to accurately report stimulus time estimation. If they learn from the training, it will indicate a level of proficiency over action-outcome time-interval estimations, leading to a boosted intentional binding effect in the active condition, suggesting they have learned a feeling of control.

The next section will consider possible covariates in this experiment that might obscure the data, based on a theoretical model of why the intentional binding happens, and why we have included an exploratory hypothesis in this experiment.

Time-Perception and the Temporal Attention Model

Previous research has investigated the mechanics of subjective time-perception and question why the Intentional Binding effect might occur; One theory evolves from the “Internal Clock” model (Zakay & Block, 1995) which postulates that one’s innate sense of time is disrupted and modulated by their *focus of attention*.

The theoretical model seeks to explain time perception and its discrepancies between individuals. To illustrate, the model includes three components: the pacemaker, the switch, and the accumulator. The pacemaker sustains the passing of time sending “pulses” to the accumulator, which gathers these pulses to estimate time. The switch changes the tempo of the passing of time when the focus of attention switches. Individual differences in time perception are thus measured by the prolongment of the pacemaker’s pulses or the latency of the switch (Donapati, R. (2024).

In relation to the Intentional Binding effect, the theory supposes that the temporal compression between intentional action and outcome is caused by the mind’s focus of attention switching to their voluntary actions and using motor-prediction to anticipate the result. The theory states the mind allocates resources to whatever event’s it deems important in that moment, thereby one experiences their action-events with a temporal shortening and unconsciously underestimates the time delay.

It should be emphasized; the temporal attention model does not explain all phenomena that causes Intentional Binding; For instance, specific event shifting, where the mind uses predictive mechanisms about time to infer sensory information, for example if one learns their actions cause an outcome (press a button hear a beep) one will perceive their intent to act as closer to the beep-time if the time is delayed (Rigoni, D., (2015).

However, the model identifies the necessity for sustained attention and proper attentional allocation to produce Intentional Binding in experimental designs, such as this experiment. It also highlights potential confounding factors, such as attentional biases or response biases, that may obscure the outcomes in an Intentional Binding experiment. This gave us incentive to consider participants that may have an impaired ability to process time.

"Time-blindness", is a central feature of patients with attention deficit hyperactivity disorder (ADHD) (Birth. K, 2017, Moccia, L. et al, 2024). Defined as a learning difficulty, deficits in working memory and attentional allocation in patients with ADHD could lead to a defective perception of time passing, thereby distorting interval estimation tasks. Hypothetically, the ADHD patient would perceive the time-delays in active and passive condition as both shorter. The literature on ADHD and impaired time-perception and differences in learning styles is well documented so recognizing this as a possible confounding factor, ADHD symptomology was screened for in this experiment. Participants with a high ADHD index can potentially modulate the intentional binding effect through learning because, despite their challenges with sustained attention and time perception, they can still benefit from structured and repetitive learning experiences and leverage neuroplasticity, allowing them to adapt their attentional focus and timing mechanisms over with practice.

Hypothesis, Aims, and Objectives

The sense of agency, which refers to the experience of controlling one's actions and their outcomes, is well-established to be modulated by experiential factors, suggesting that it can be influenced through learning processes. This study aims to demonstrate that a structured learning procedure is sufficient to induce the intentional binding (IB) effect.

Hypothesis

The primary hypothesis posits that a structured learning procedure will modulate the intentional binding effect. The training procedure was designed to familiarize participants with the passage of time during both active and passive trials by providing exposure and brief practice sessions before the commencement of the experiment. The experimental design employed a computer-based setup, replicating previous studies on intentional binding. In this setup, the IB effect was assessed by having participants press a key to elicit an auditory tone and subsequently report their experience. Participants were assigned to one of two learning groups, corresponding to either the 300ms or 900ms condition, to evaluate whether familiarity with specific time delays would result in an increased intentional binding effect when re-exposed to the same delay. This approach aims to demonstrate that participants have effectively learned the timing intervals.

It is predicted that participants in the 300ms training group will exhibit a larger IB effect when the tone occurs in active trials after 300ms, while those in the 900ms training group will demonstrate a larger IB effect when the tone occurs after 900ms. No cross-over effects of training are expected between groups due to the lack of exposure to alternate time delays.

It is not anticipated that changes will occur in the control trials, which involve no active response from participants (i.e., no keypress condition), as these should not produce the intentional binding effect. Should changes be observed in the control condition, it would suggest that participants have become more precise in their time perceptions due to passive learning rather than intentional binding. Such findings would indicate that any observed effects in the control condition are related to improvements in time perception accuracy rather than intentional agency.

The exploratory hypothesis suggests that ADHD will act as an extenuating variable in the experiment. Participants' ADHD symptomatology will be controlled through an initial standardized ADHD questionnaire. Given that ADHD is a neurodevelopmental disorder associated with learning difficulties, it is anticipated that participants with symptoms of inattentiveness and time-blindness will face challenges in accurately reporting events in milliseconds during an interval estimation method experiment (Birth, 2017). Consequently, it is expected that participants with a high ADHD index will exhibit little to no intentional binding in active task conditions.

The study's objectives are as follows:

- First, to determine whether a structured learning procedure can modulate the intentional binding effect.
- Secondly, to compare the intentional binding effect between participants trained on different time delays (300ms vs. 900ms).
- Thirdly, to explore the influence of ADHD on the intentional binding effect.

Materials and Methods

Participants

Participants were recruited through Prolific (www.prolific.com), an online platform designed to help researchers recruit participants for their studies quickly and efficiently. Prolific allowed researchers to obtain a diverse pool of vetted participants for this experiment, ensuring the data collected is high-quality and representative of the population.

Eligibility criteria included being 18 years or older, having the ability to understand English, and lacking any physical impairments that would prevent the use of a keyboard or inhibit reaction time. A demographics questionnaire collected data on age (18-51+), gender, ethnicity, and previous ADHD diagnosis.

Additionally, participants were screened for ADHD using the Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist, which measured inattention severity over the past six months on a scale from "never" to "very often".

Based on prior literature and the study's objectives, a sample size of 60 participants was determined to be sufficient.

Participants were fully informed about the study's purpose, hypotheses, and procedures, and they were given the opportunity to contact researchers for further information or to discuss any concerns. They were assured of their right to withdraw at any time.

Confidentiality of personal information and results was emphasized, with details provided about the data protection policy and contacts for the ethics officer and complaint department.

Procedure

Ethical Approval

All procedures received approval from the Birkbeck ethics committee.

Participant Recruitment and Consent (sampling procedure)

Participants were recruited via Prolific and provided with detailed information about the experiment upon clicking the survey link. *(Prolific is an online recruitment platform used to vet and ensure legitimate and ethical sampling, and allows the researchers to pay for participants time)*

Each participant reviewed and completed a consent form ensuring informed participation. Each participant was assigned a unique Prolific ID for tracking and compensation purposes.

Sample Size, Power, and Precision

To balance accuracy and resource use, we determined the sample size to be 60 participants. We based this sample size on a modified version of the same experiment by Seghezzi. S, (2020) that also used a sample size of 60.

Power was set at 0.80 to reduce the likelihood of Type II errors, calculated based on expected effect size and significance level.

The precision of our estimates was enhanced by including a sample size to 60, which reduced the standard error and, consequently, the width of the confidence intervals. We aimed to achieve a balance between sufficient precision and feasible resource allocation.

Measures and Covariates

Our primary measure was the intentional binding effect. This is described in the data at the intentional binding index (IBI).

Our secondary measure was assessing changes in the intentional binding effect over time as participants undergo the initial learning procedure. The intentional binding effect was measured at multiple points during the learning procedure to assess changes over time.

Another secondary measure was participant time; we recorded the time taken to complete the entire experiment and were able to assess how long it took each participant.

The covariates collecting in this study include participants age, gender, ethnicity, English language fluency, ADHD diagnosis and their self-reported experience of ADHD.

Data Collection

Data was collected from an online recruitment platform, Prolific, which automatically recorded data during experiment. We chose Prolific specifically, as it has been shown to recruit a wide range of participants globally and allowed us to find the number of participants needed to reach the samples size within a few days.

Prolific was designed by researchers specifically to recruit subjects for behavioural online experimentation, which makes it an ideal choice for this study.

Quality of Measurements

We ensured the quality of our data by providing clear written instructions that were concise, and available throughout the experiment for reference.

We also included practice trials before the actual experiment begins. These trials helped participants familiarize themselves with the task requirements and interface.

We used Prolific pre-screening tools to screen for participants with ADHD and ensure that they had a good grasp of the English language.

To ensure participants were engaged and paying attention we placed a 50-minute time-limitation on the experiment, which meant that they could not pause the experiment and return later and had to complete the task in one attempt. The time limitation ruled out any irregularities or suspicious behaviour.

We implement a repeated measures design where each participant completes multiple trials of the intentional binding task. This helps to account for variability and enhances the reliability of the measurements.

We used data averaging to calculate the intentional binding effect by averaging the mean responses across multiple trials for each participant. This reduces the impact of outliers and random errors. We also analysed the consistency of participant responses across trials to identify and exclude inconsistent data.

We used automated scripts to validate data for completeness and logical consistency (e.g., ensuring time intervals fall within expected ranges) and check for any anomalies or patterns indicating low-quality responses. We also implemented statistical methods to detect and handle outliers, ensuring they do not skew the results.

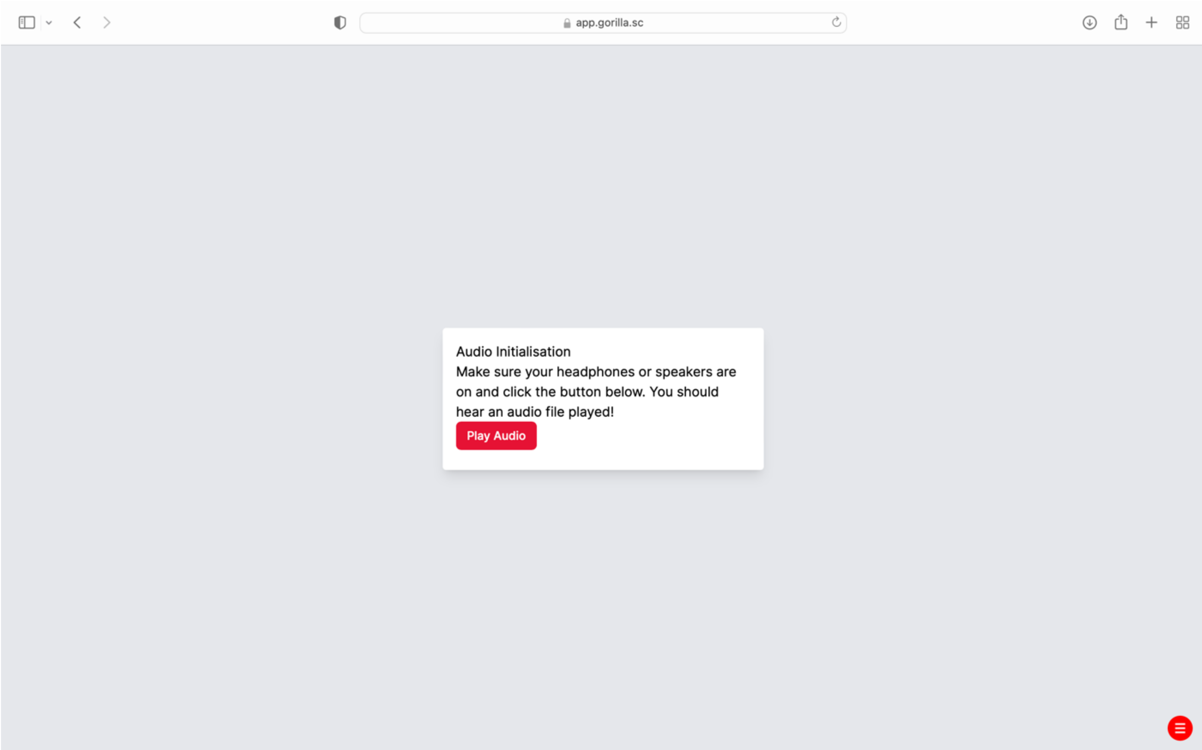
Platform and Equipment Requirements

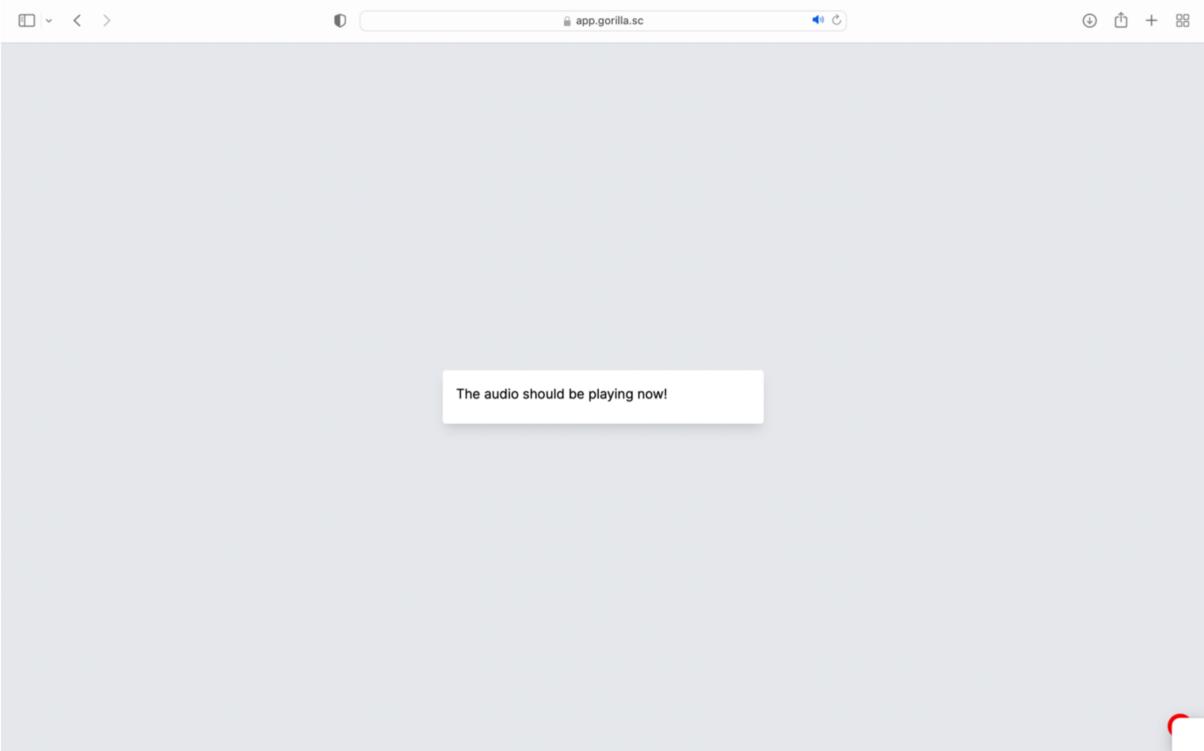
Participants agreeing to the study were redirected to Gorilla Experiment Builder, an online platform for designing behavioural experiments.

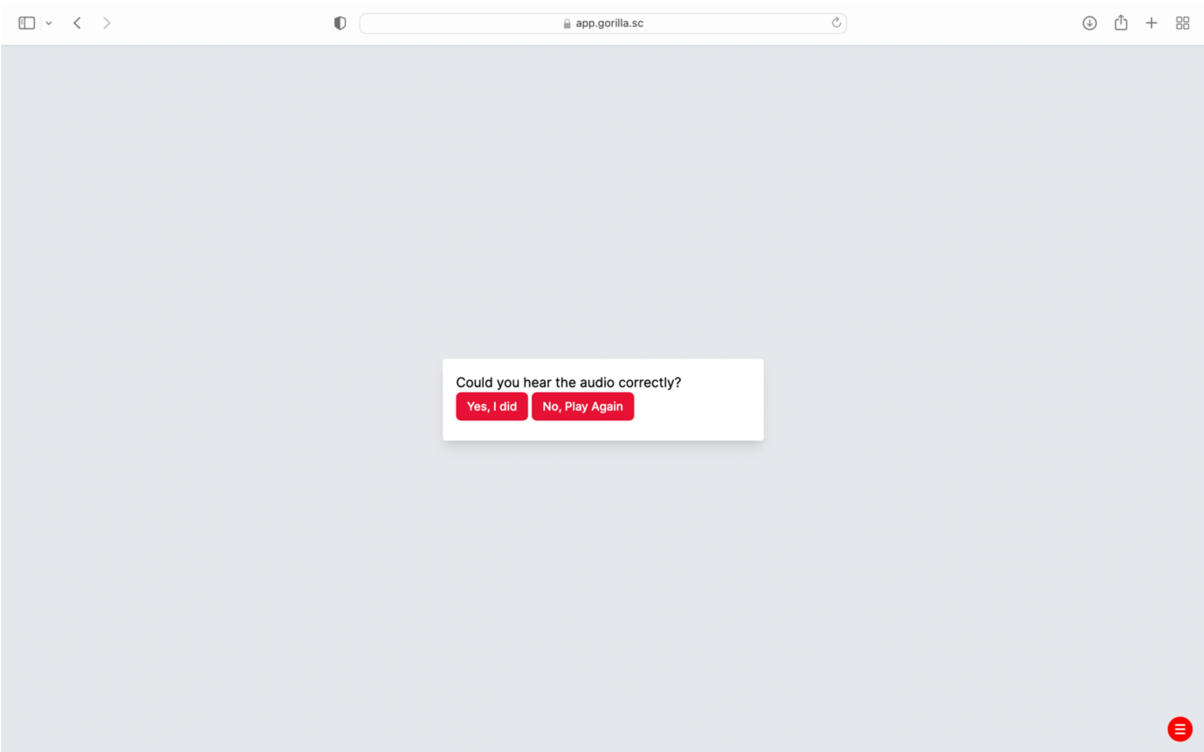
To maintain consistency and data quality, mobile phone submissions were not permitted.

Participants were required to use headphones and a standard keyboard. A brief sound check ensured proper headphone functionality, where participants confirmed hearing a “1,2,3” audio clip (500Hz tones, each lasting 50ms, presented every 500ms). Successful completion allowed them to proceed.

The slide visualization is shown here:







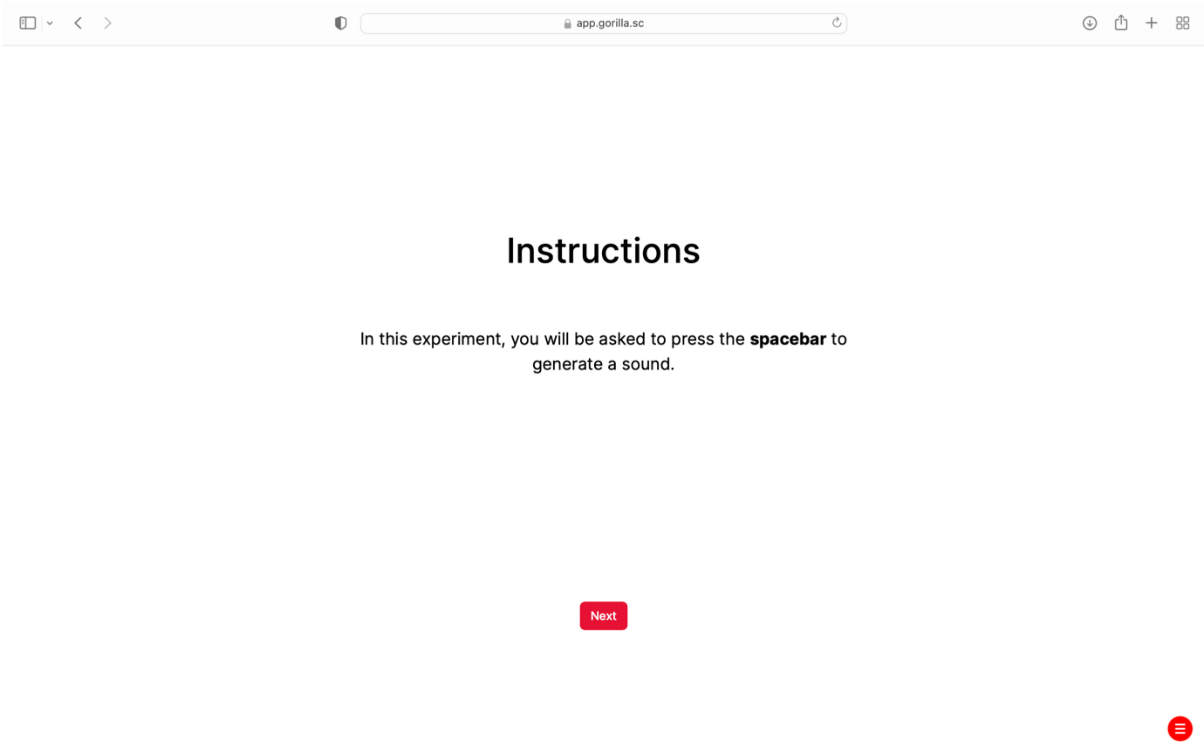
Identification and Compensation

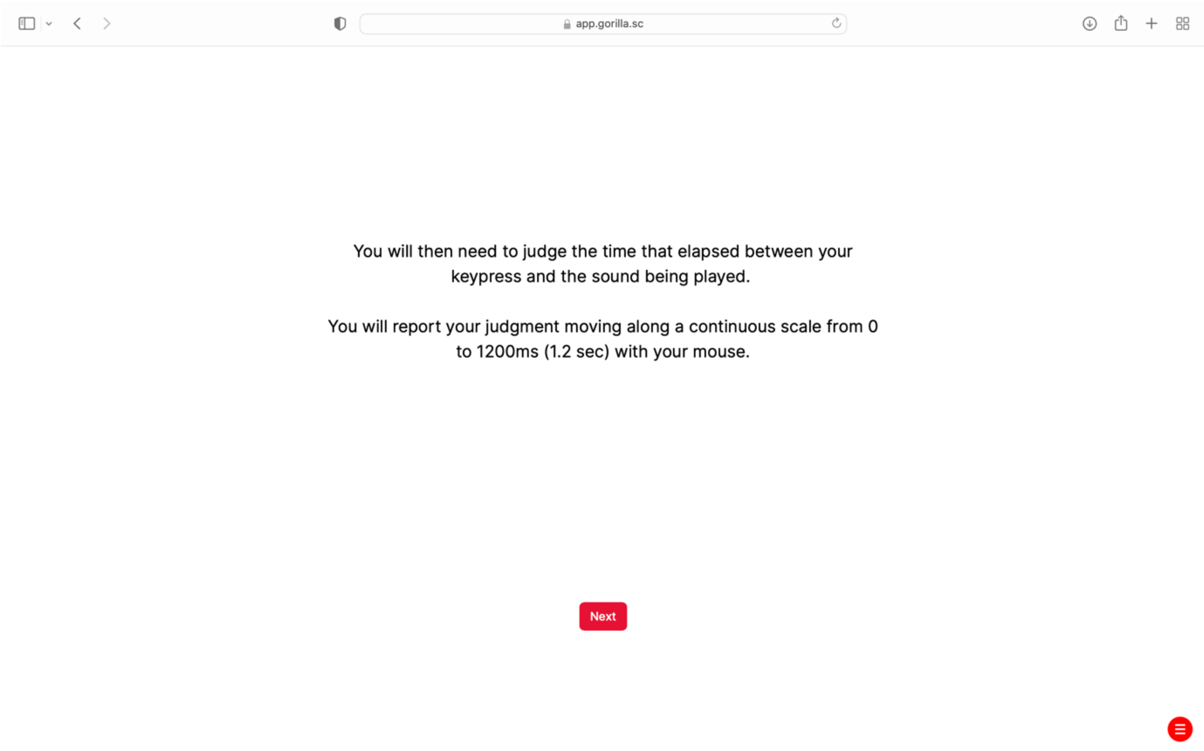
Participants entered their Prolific ID before starting the experiment. Upon completion, they received a code for payment, with a base rate of £7.00 and a potential performance bonuses.

Task

The task was based on a modified version of an intentional binding and learning task used in previous research by Seghezzi et al. (2023); the independent variable was a learning procedure and feedback conditions in either 300ms, 600ms and 900ms. The dependant variable was the time delay.

The task instruction visualization is shown here:





Learning Trial

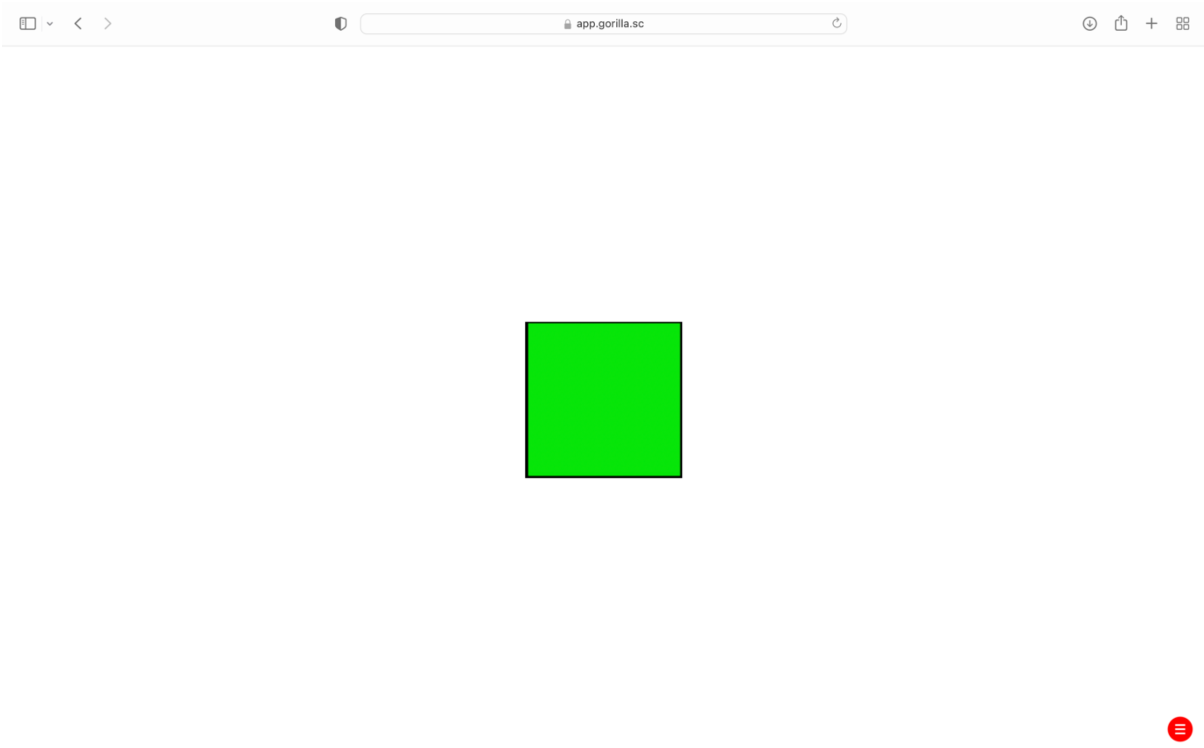
In the learning trial, participants were randomly assigned to two groups: a 300ms or 900ms sound delay task.

Action Trial

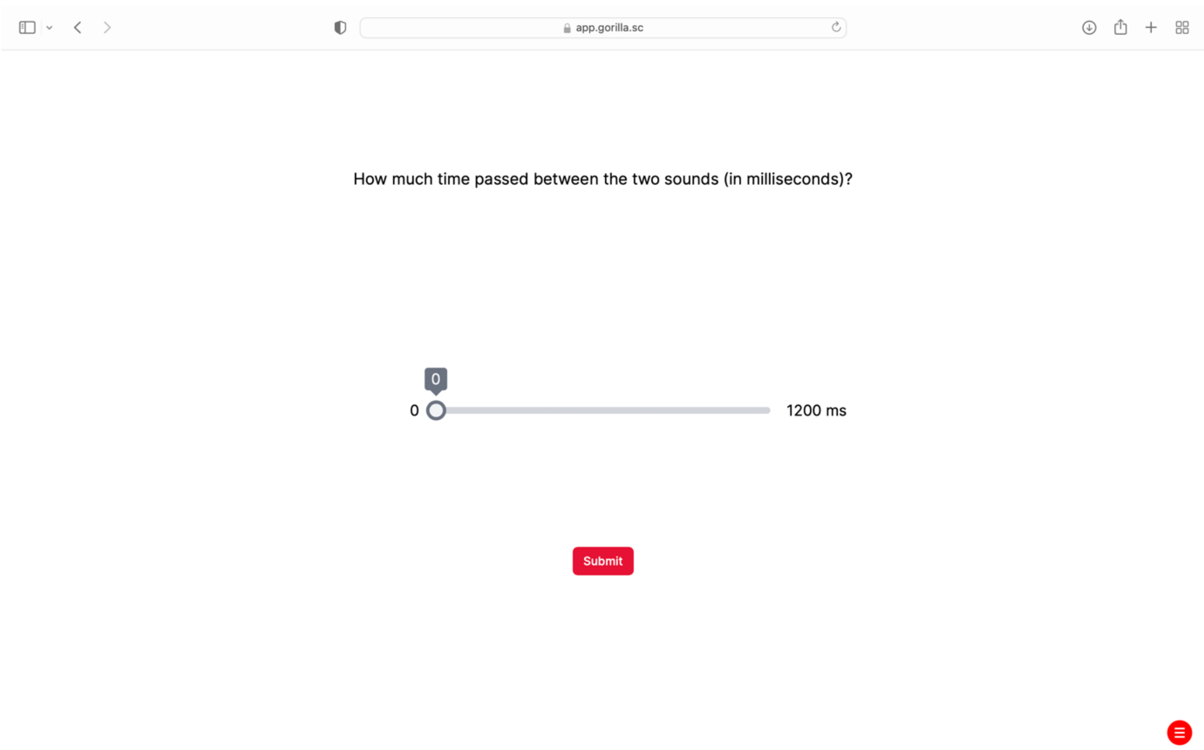
The task first involved a learning procedure, to familiarise participant with the trails.

Participants saw a green square and pressed the spacebar, followed by an auditory tone (500Hz, 50ms) after either a 300ms, 600sm or 900ms delay.

The Action-task visualization is shown here:



They judged the elapsed time between keypress and tone, reporting their judgment in milliseconds using a continuous scale from 0 to 1.2 seconds. The scale had markings at the endpoints to guide estimation. The visualization for the timescale is shown here:

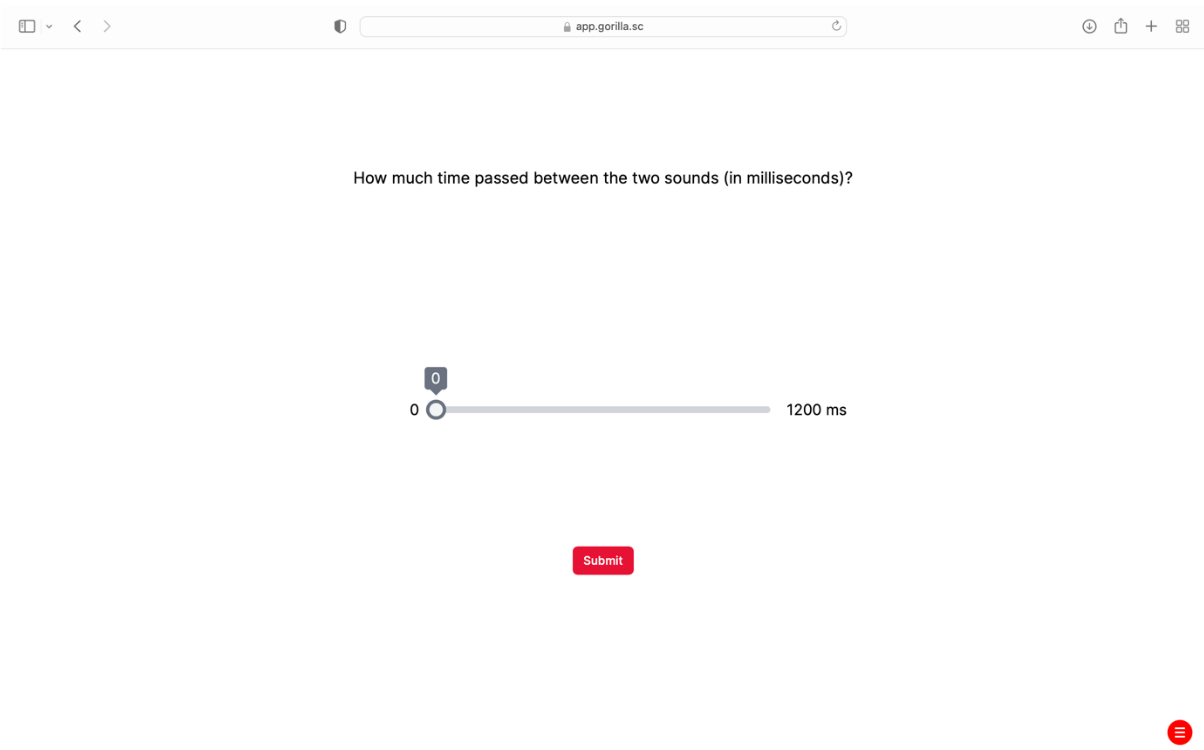


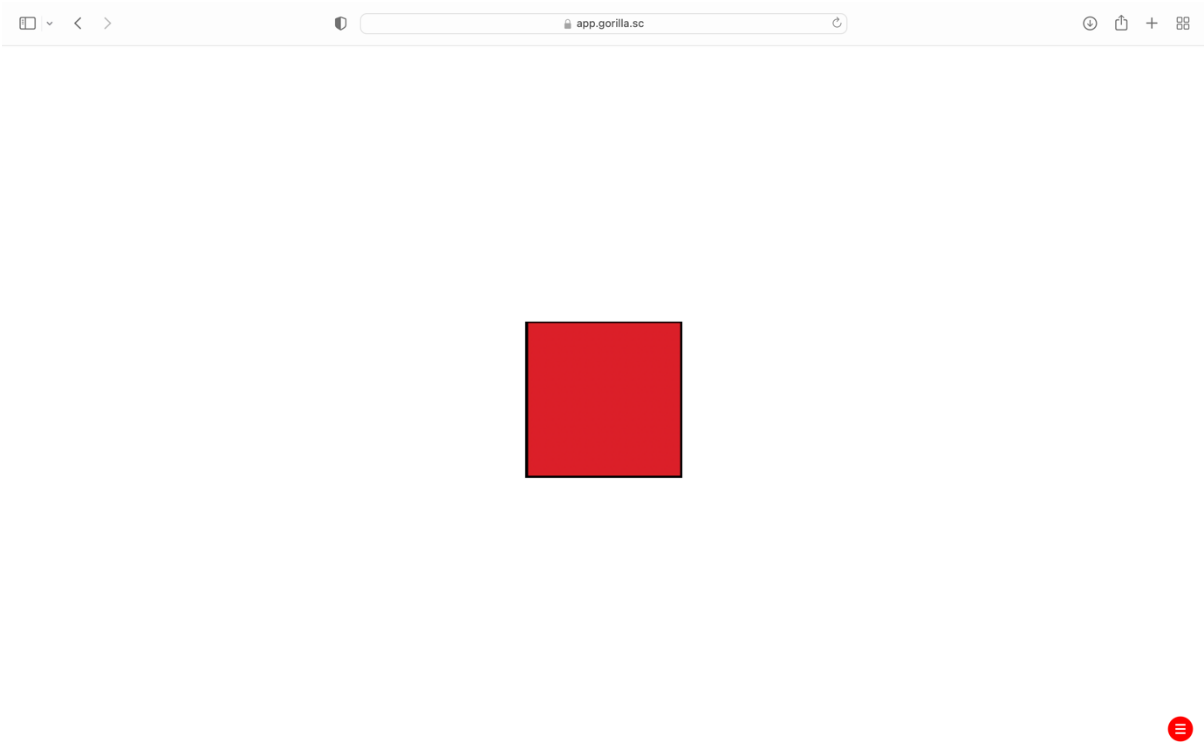
The learning trial was practiced three times before entering the experiment.

Control Trial

In the control condition, participants did not perform any actions.

They estimated the time interval between two auditory tones (500Hz, 50ms) following a red square appearance, with delays matching the active condition (300ms, 600ms or 900ms). The visualization for the Control-task is shown here:





They used the same continuous scale for estimation at the active task. The visualization for the timescale is shown here:

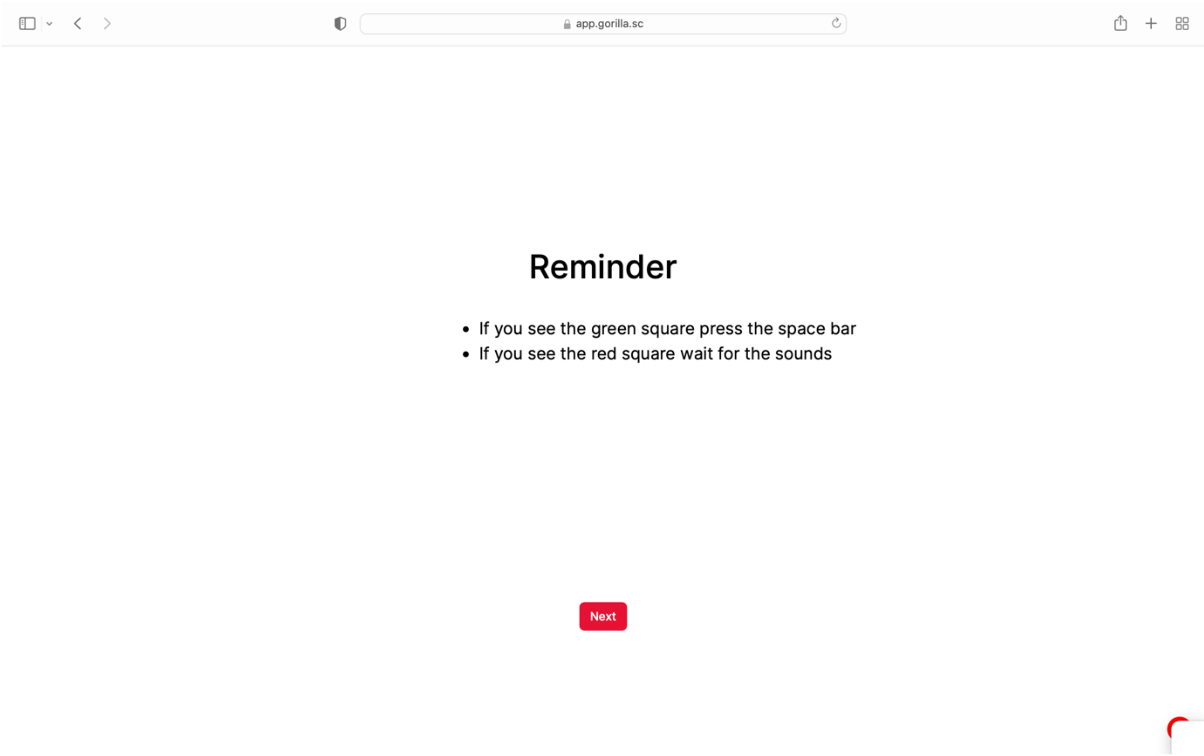
Participants completed a training block of three tasks (300ms and 900ms time delay) to ensure understanding before entering the experiment.

Experimental Trial

Participants were reminded of the task rules: green square for keypress, red square for tone waiting.

Tasks appeared in a random, unpredictable order.

The visualization for the instructions is shown here:



The Intentional Binding Effect

The experiment aimed to measure the Intentional Binding Effect (Haggard, 2002) by comparing time interval estimations in voluntary action-to-outcome conditions versus involuntary tone-to-tone conditions.

Statistical Analysis

Statistical analyses included calculating means and standard deviations for time estimations, comparing the differences between the action and control conditions to produce the intentional binding index and correlating ADHD symptom severity as a covariant with task performance using regression analysis.

Instrumentation

We used SPSS and R software for data analysis and graphical representation of the results.

Results

Participant Flow

The 60 participants were divided into two equal groups (30 each) and recruiting for our sample size took four days.

Recruitment

Recruitment dates were the 8th to the 12th of July 2024.

Statistics and Data Analysis

Statistical significance was marked as (p = 0.05).

We assume that the data is normally distributed (according to the theory of central tendency, specifically the Central Limit Theorem) and reason that the sample size of 60 is substantial enough for this particular use of mathematics to apply. (Although there no exact rule for what constitutes as a sufficient sample size, APA guidelines suggest the Central Limit Theorem holds in a sample size of at least 30).

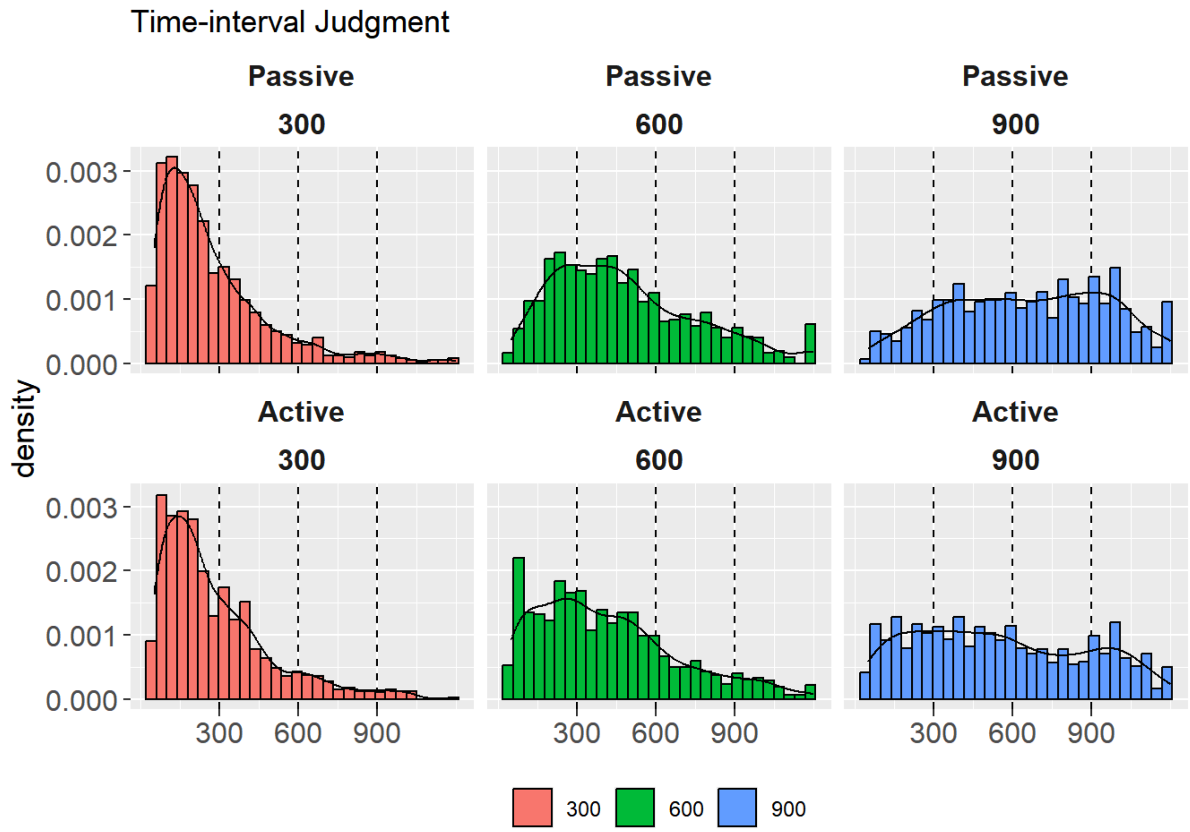
Measures

We are going to explore two main measures:

- *Time judgment*: Participants used a slider (0 to 1200 ms) to estimate the time interval between event 1 (either button press or a tone) and event 2.This measure is a continuous numerical variable.
- *Judgment error*: This is calculated as the difference between the actual feedback time and the estimated time (feedback time - time judgment). If participants can accurately perform the task, we would expect the judgment error to be around zero for both active and passive conditions. A positive error indicates that participants underestimated the actual feedback time. For example, if the feedback was delivered at 300 ms, they would estimate an interval smaller than 300 ms. This underestimation is expected, especially in the active condition, due to the intentional binding effect. In other words, we expect judgment errors in the active condition to be more positive than those in the passive condition.

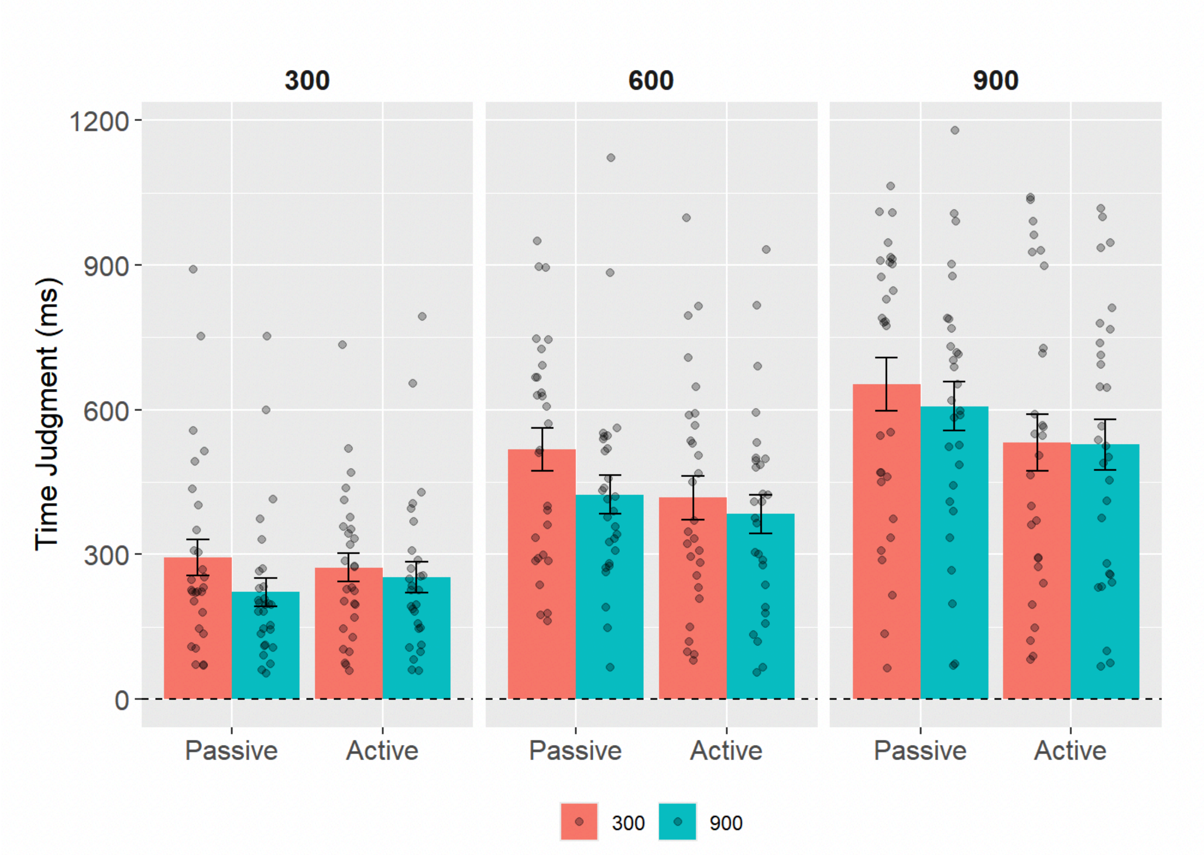
Descriptive Statistics

Time-interval Judgment Graph



Graph 1: To show the distributions of participants' judgments for time intervals under Passive and Active conditions at different time lengths (300 ms, 600 ms, 900 ms).

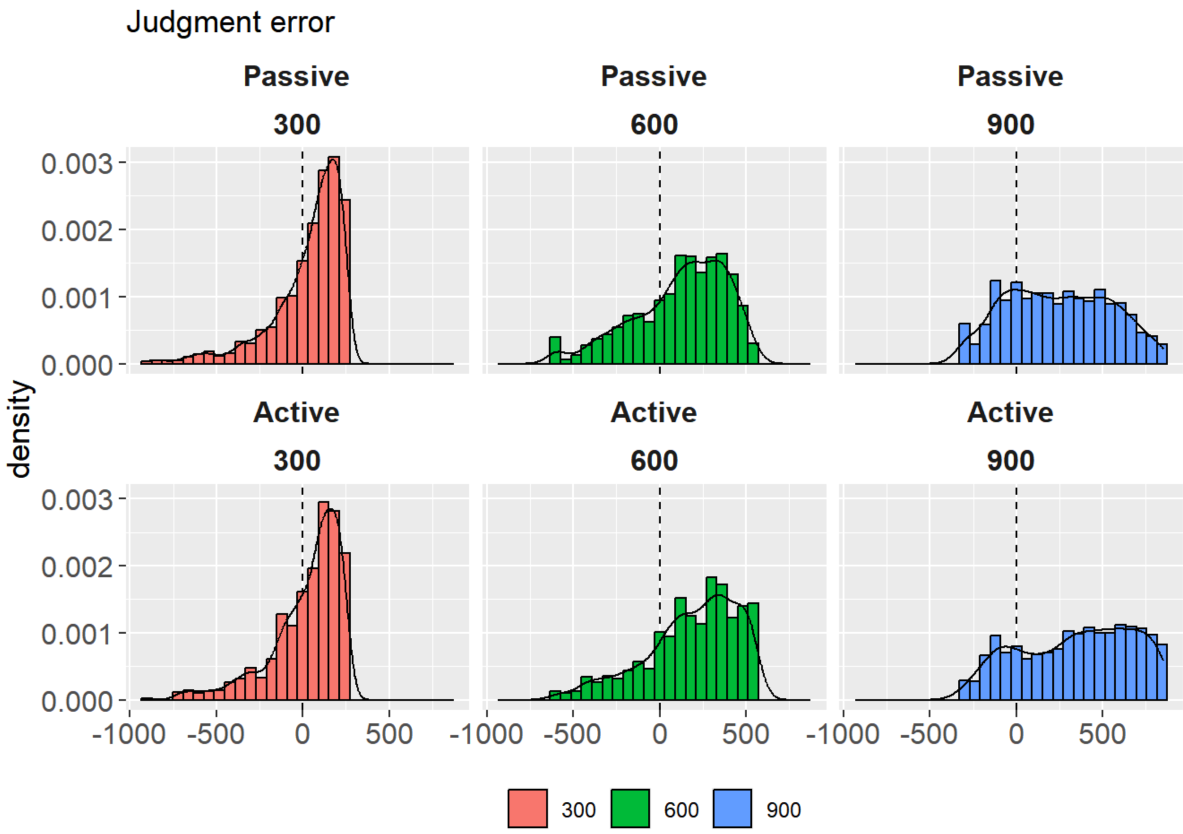
From the plots above, participants generally underestimated the time interval, especially for the 300 ms and 600 ms feedback conditions. In other words, when the feedback (the tone) was delivered at 300 ms, participants reported it as occurring earlier. The same pattern was observed for the 600 ms feedback. Additionally, the distribution of time-interval judgments is more skewed for the 300 ms feedback.



Graph 2: To show a comparison of time judgments (in milliseconds, ms) between two different conditions: "Passive" and "Active," across three different intervals or categories labeled 300ms, 600ms, and 900ms.

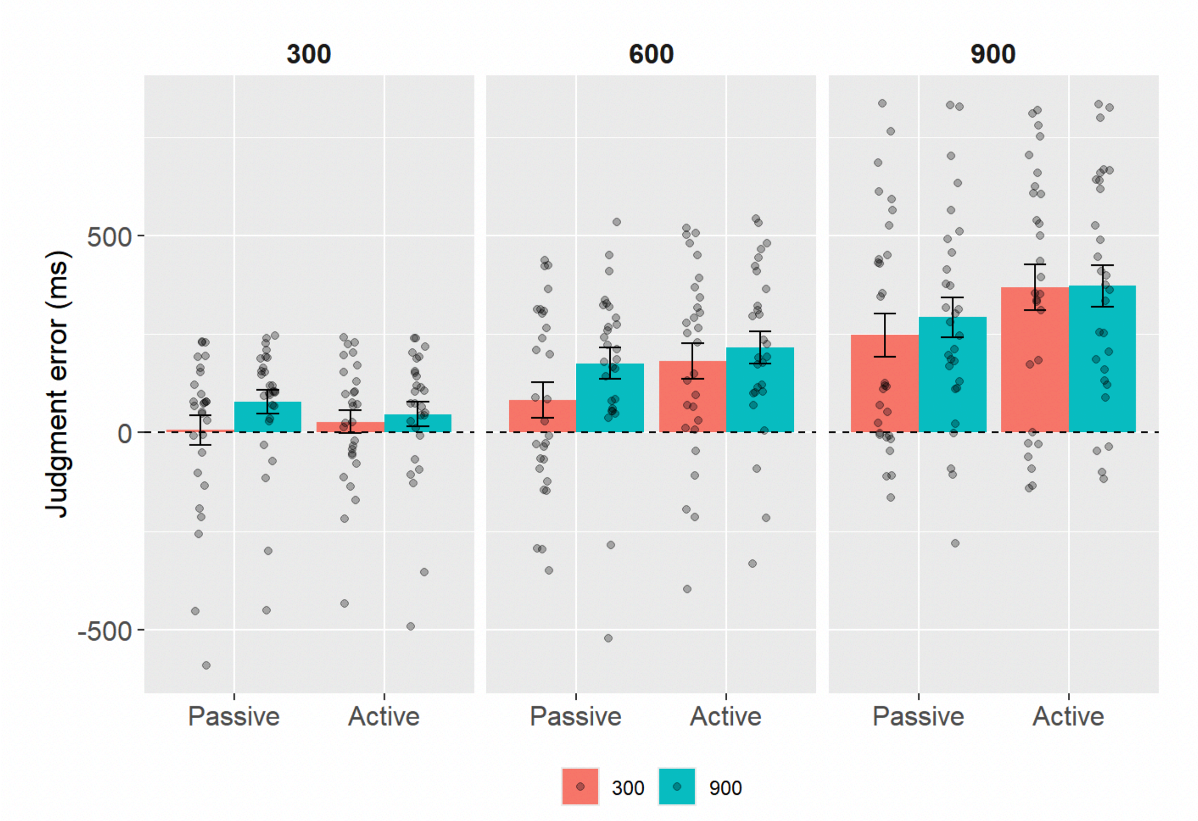
This suggests that time judgment differs between the "Passive" and "Active" conditions, and that this difference is more pronounced for longer time intervals (600 and 900 ms).

Judgment error



Graph 3: This graph represents the distribution of judgment errors in estimating time intervals under different conditions.

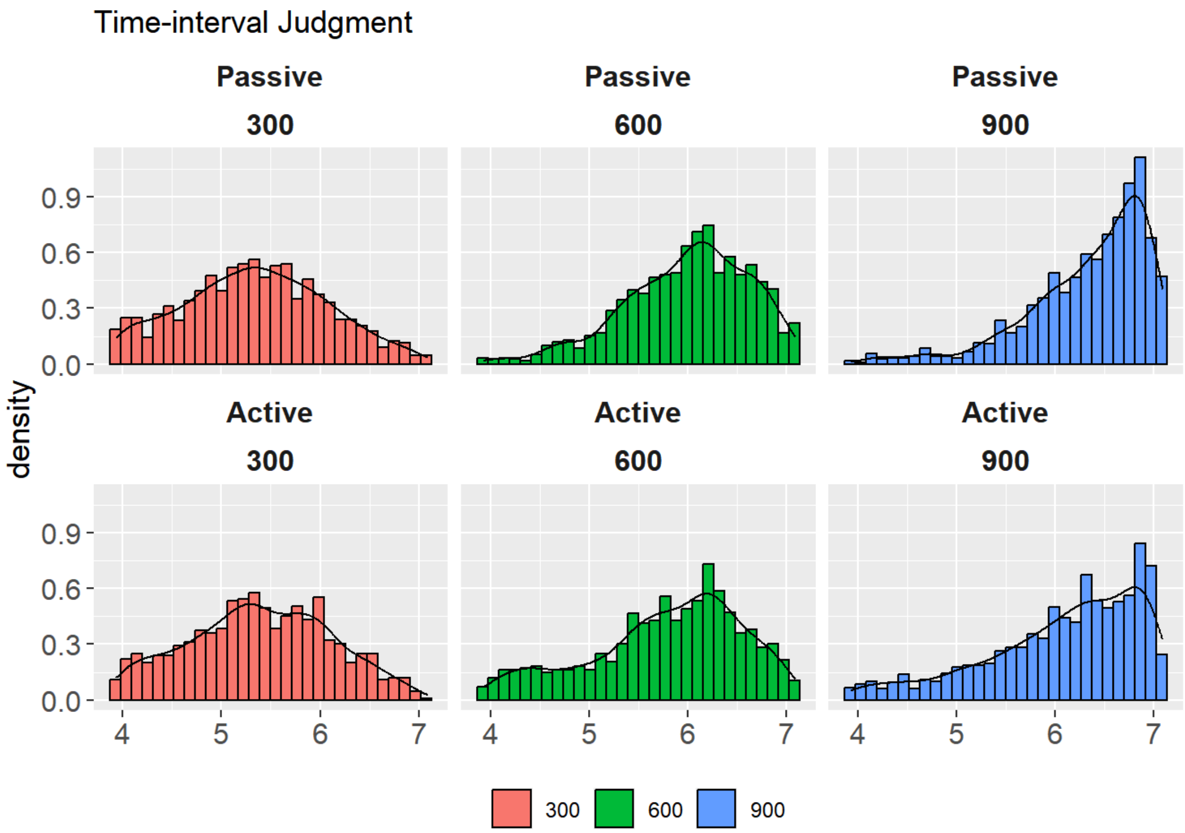
The distributions of the judgment errors confirmed what already reported in the time judgment plots. Errors are generally positive, indicating that participants underestimated the time interval between event 1 and event 2.



Graph 4: Depicts the relationship between "Judgment Error (ms)" on the y-axis and different conditions on the x-axis.

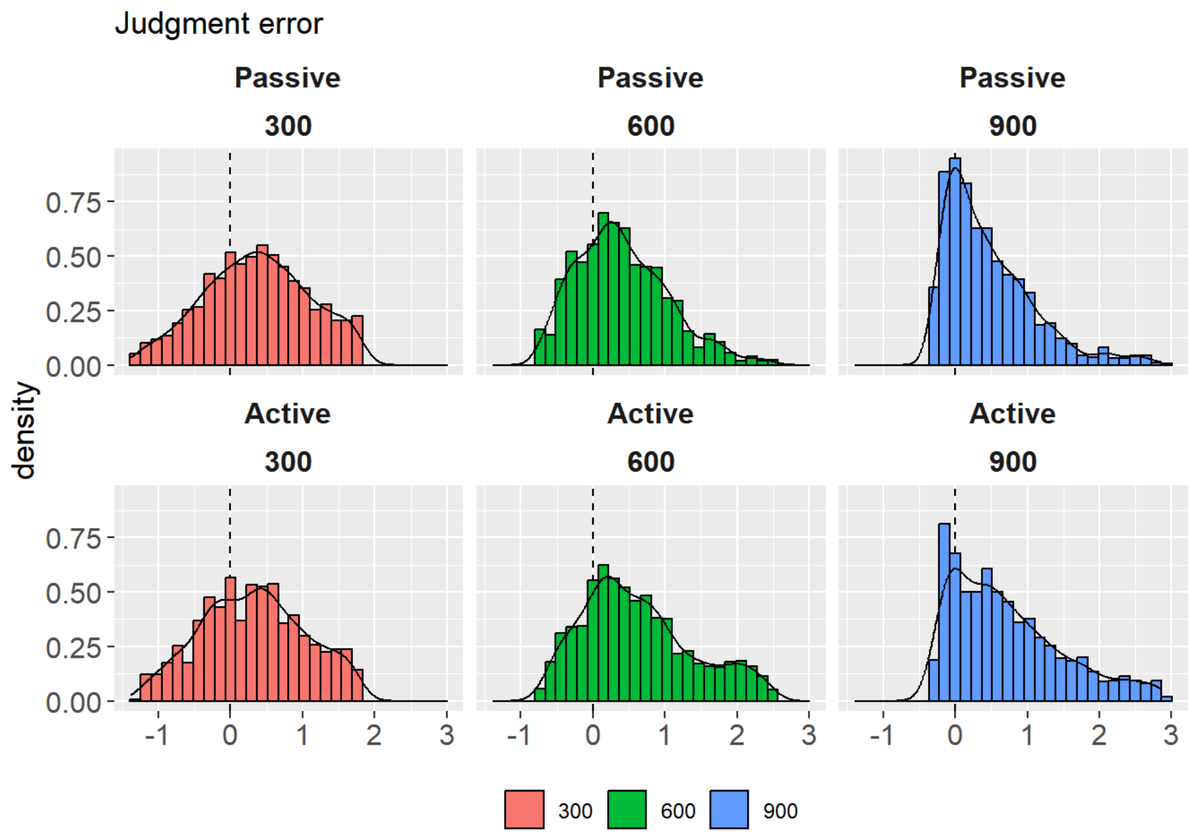
ADHD Covariate

LOG Time-interval Judgment



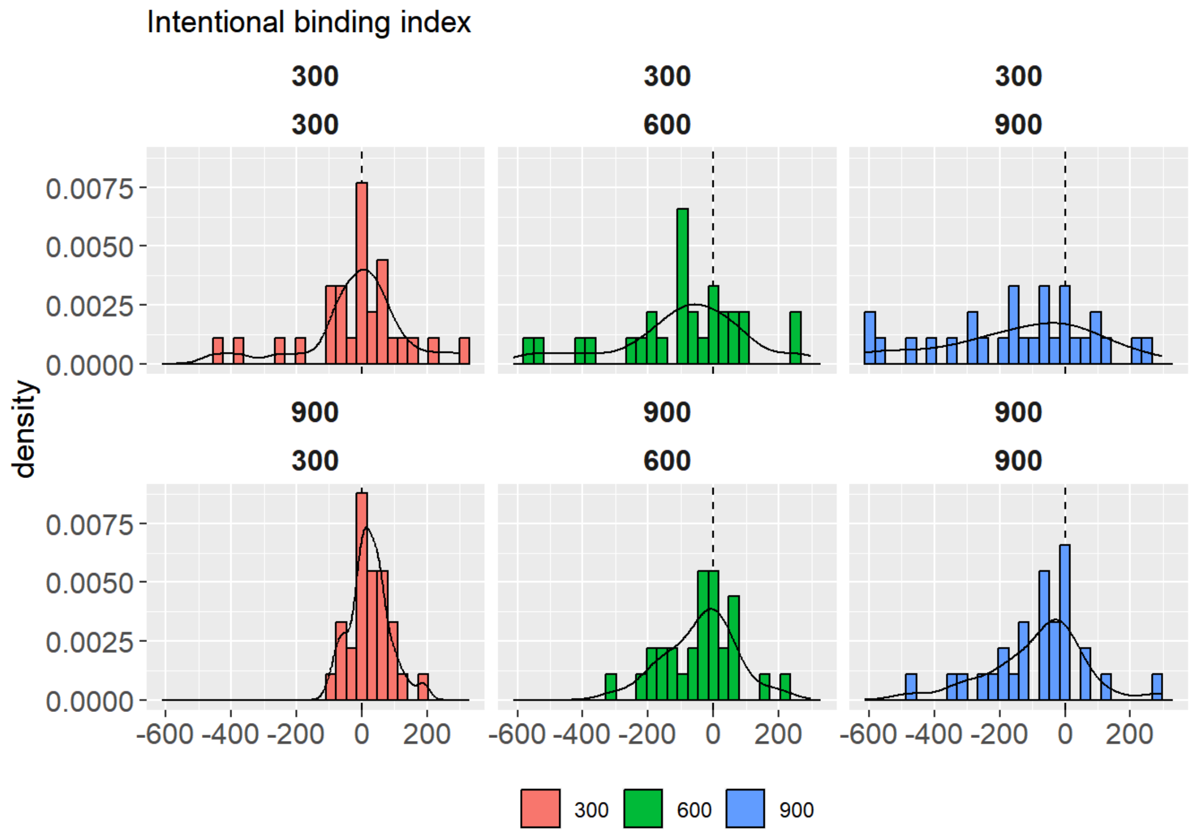
Graph 5: Graph to represent the log-transformed distribution of time-interval judgments across different conditions.

LOG Judgment error



Graph 6: This graph represents the distribution of judgment errors in different conditions, showing how participants estimated time intervals.

The Intentional Binding Index



Graph 7: This graph represents the Intentional Binding Index distributions for different conditions and time intervals.

Analyses

We expect an increased intentional binding effect (i.e., greater difference between passive and active time judgments) at the feedback time corresponding to the participants' training. Specifically, for the group that trained with 300 ms feedback, we anticipate a larger difference between passive and active conditions at 300 ms feedback compared to the group that trained with 600 ms feedback. This difference could arise either from more time compression in the active condition or more time dilation in the passive condition. Similarly, we expect a larger effect in the 600 ms training group when tested with 600 ms feedback, compared to the 300 ms training group.

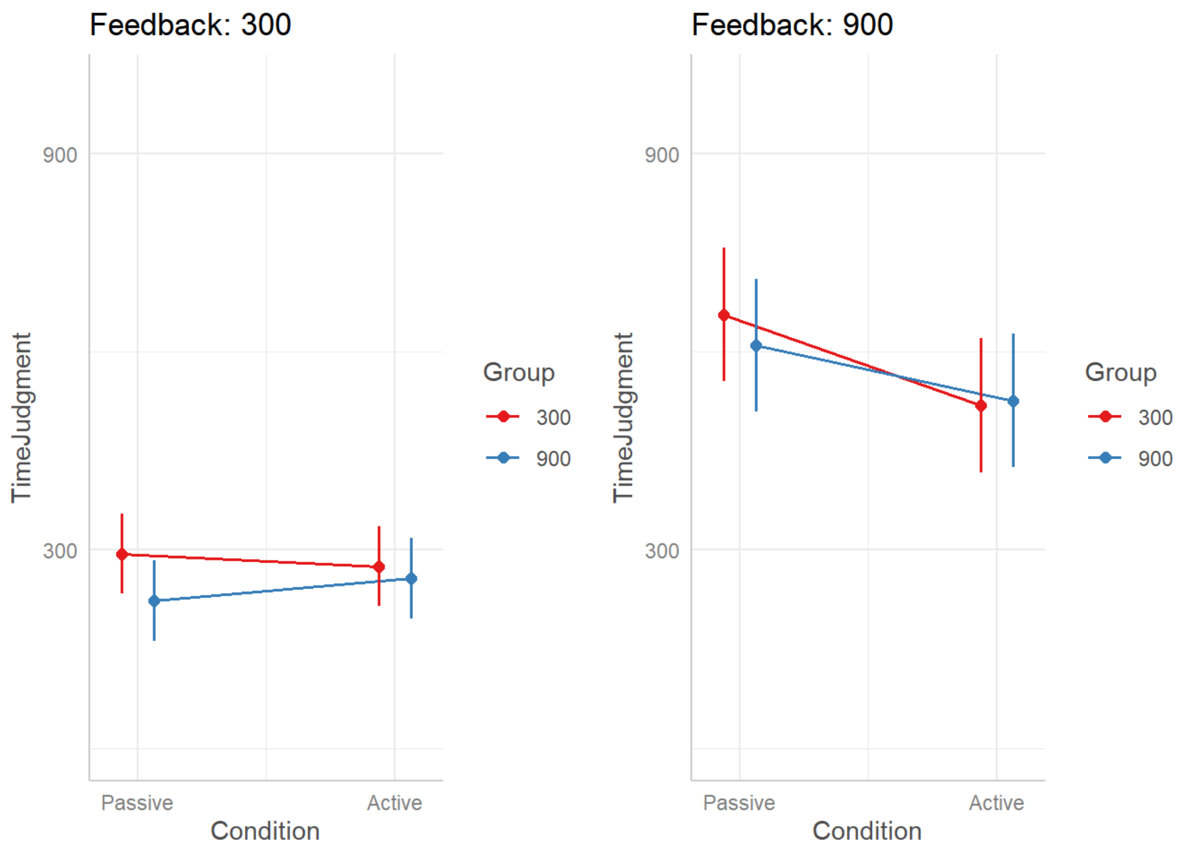
Two-way (splitted feedback) with ADHD

To estimate the training effect, we analysed the two feedback conditions separately. In this way, the group that did not train at that feedback condition would act as a control group, as we expect no changes due to training for them.

We conducted a two two-way anovas for each feedback condition with group (300, 600) and condition (passive, active) and their interaction as factor of interests. We also included the ADHD index as a covariate.

This suggests that the training effectively modified the typical effects observed. To further explore this interaction, let's examine the effect plots.

Plots



Graph 8: This represents time judgment across different conditions under varying feedback scenarios. (NOTE: Results may be misleading due to involvement in interactions)

First, note that time judgments differed between the two feedback conditions as expected: participants judged shorter time intervals for the 300 ms condition and longer intervals for the 900 ms condition. Interestingly, participants were generally accurate in the 300 ms feedback condition (262.67ms), with an average judgment error of 37.33ms. In contrast, for the 900 ms feedback condition 577.7379517ms, participants showed an average judgment error of 322.26ms. Another point to note is the difference between the passive and active conditions, which is evident in the 900 ms feedback for both groups and resulted in a main effect of condition (Condition: $F(1.00,2117.51)=193.72$, $p<0.001$).

However, this difference is more subtle for the 300 ms feedback, and no main effect of condition was observed (Condition: $F(1.00,1965.41)=1.47$, $p=0.226$). Interestingly, while the difference between passive and active conditions follows the expected pattern for the 300 ms group (Diff=18.21ms; Group: 300 - Passive vs Active: $t(1967.77)=2.27$, $p=0.023$), indicating a small but significant intentional binding effect, no intentional binding effect was observed for the 900 ms training group. In fact, the effect was in the opposite direction (Diff=-33.46ms; Group: 300 - Passive vs Active: $t(2120.60)=12.26$, $p<0.001$). We then examined the difference between the two groups separately for the active and passive conditions and across the two feedback conditions. For the 300 ms feedback, in the passive condition, the difference between the 300 ms and 900 ms groups was positive but not significant (Diff=70.54ms; Passive - Group: 300 vs 900: $t(53.88)=1.61$, $p=0.114$); Similarly, in the active condition, the difference between the two groups was positive but not significant (Diff=18.21ms; Active - Group: 300 vs 900: $t(54.07)=0.41$, $p=0.680$).

These results suggest that participants who trained at 300 ms developed a intentional binding effect after the training. However, the results also suggest that they improved their ability to accurately judge the interval in the passive condition relative to the other group, while less change was observed in the active condition. This indicates perceptual learning rather than an increased intentional binding effect. However, these findings should be interpreted with caution, as they were not statistically significant. Therefore, it is more appropriate to say that the observed developed intentional binding effect is the result of the combination of both perceptual learning and increased intentional binding effect.

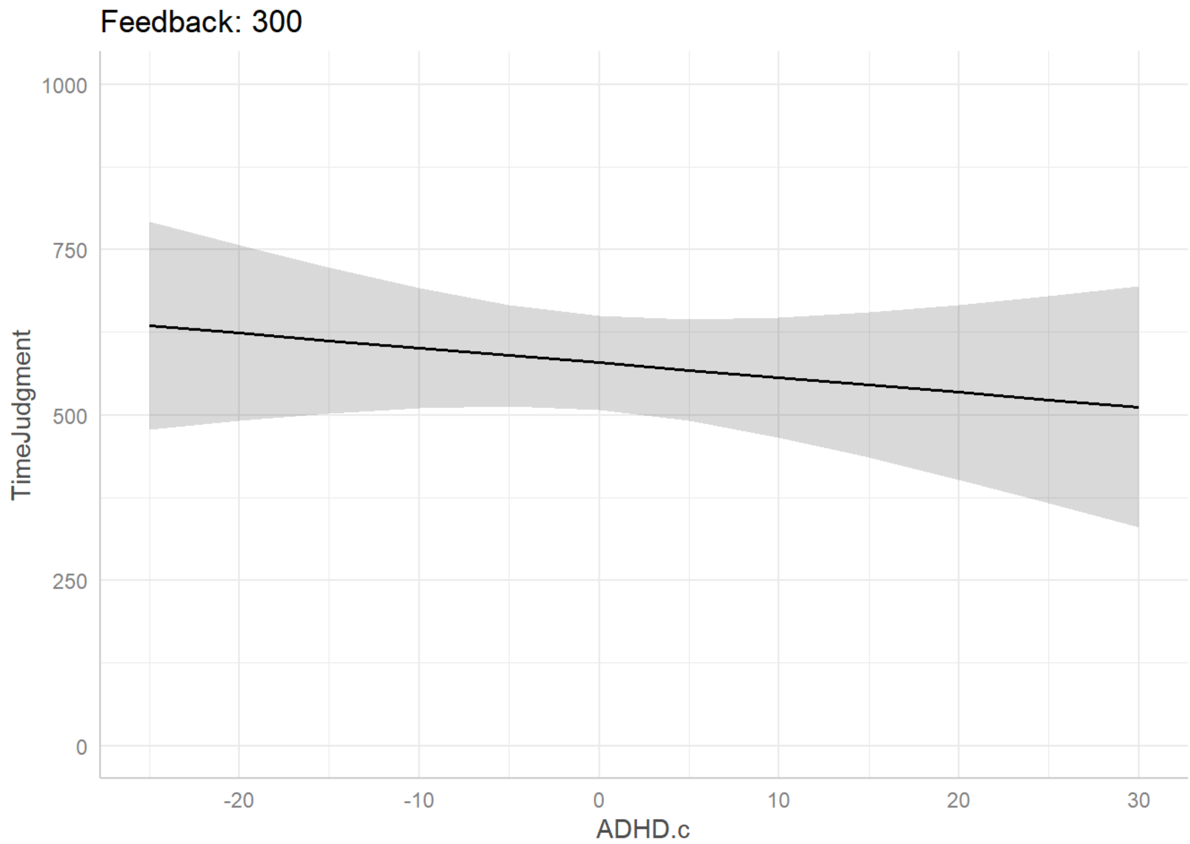
As mentioned earlier, the intentional binding effect was evident in the 900 ms feedback for both groups (Condition: $F(1.00,2117.51)=193.72$, $p<0.001$). However, we also observed a significant two-way interaction between group and condition (Group:Condition: $F(1.00,2119.21)=10.99$, $p<0.001$). Both groups showed a significant difference between the active and passive conditions, with the 300 ms group showing a larger effect (Diff=137.27ms; Group: 300 - Passive vs Active: $t(2120.60)=12.26$, $p<0.001$) compared to the 900 ms group (Diff=83.83ms; Group: 300 - Passive vs Active: $t(2120.60)=12.26$, $p<0.001$). When comparing the 300 ms and 900 ms groups in the passive condition, the difference was positive but not significant (Diff=46.46ms; Passive - Group: 300 vs 900: $t(53.93)=0.64$, $p=0.526$). In the active condition, the difference between the two groups was negative but not significant (Diff=-6.98ms; Active - Group: 300 vs 900: $t(54.08)=-0.10$, $p=0.924$). These results suggest that training does modulate the intentional binding effect at 900 ms feedback, but it appears to reduce the effect.

ADHD

Next, we will explore how attention mechanisms, as measured by the ADHD index, influence the intentional binding effects. We observed a three-way interaction between group, condition, and ADHD index at both the 300 ms feedback (Group:Condition:ADHD.c: $F(1.00,1969.77)=24.03$, $p<0.001$) and the 900 ms feedback (Group:Condition:ADHD.c: $F(1.00,2116.69)=17.63$, $p<0.001$).

To better understand the impact of the ADHD index, let's examine some plots.

Plots

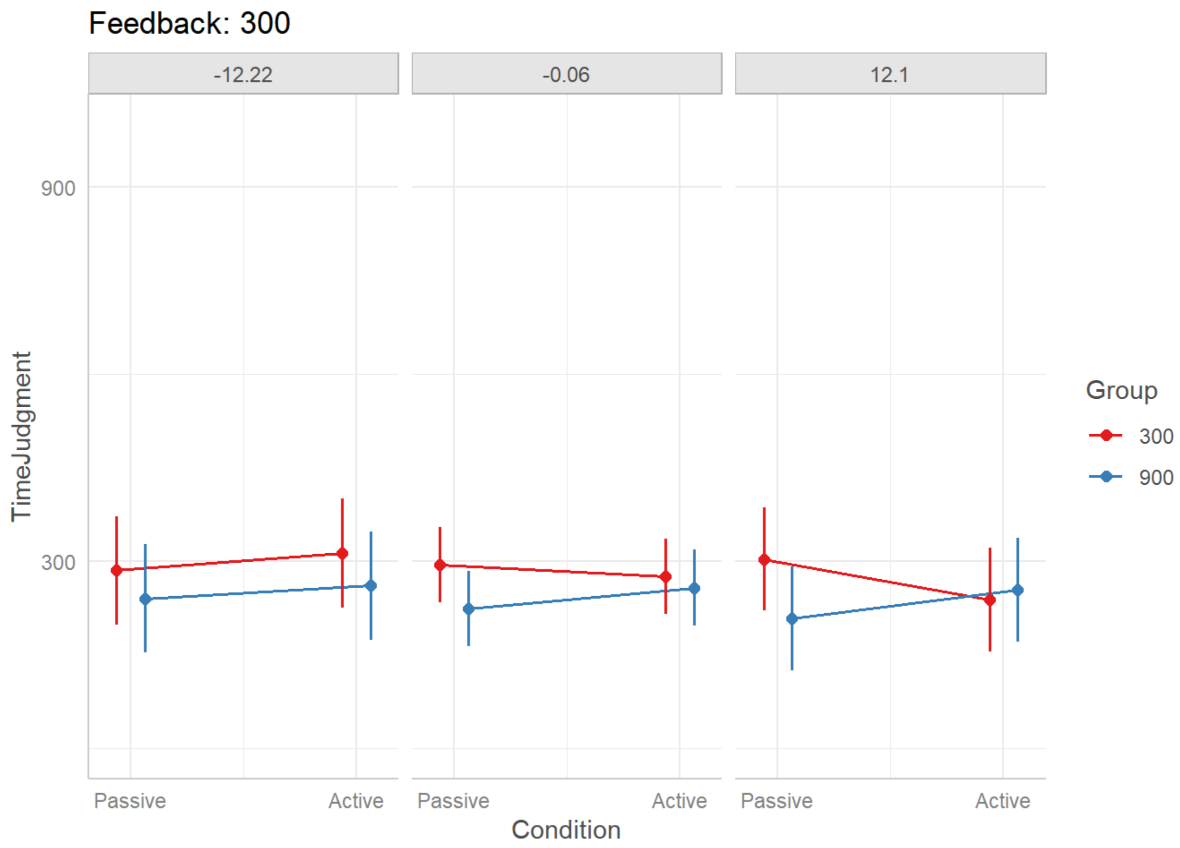


Plot 1: This plot represents the relationship between ADHD scores (ADHD.c) and Time Judgment under the Feedback.

This plot shows a weak correlation between ADHD and time-judgement.

Plot 2: This plot represents the relationship between ADHD scores and Time Judgment under two different conditions: Passive and Active.

In general, higher values of ADHD predicted smaller time-interval judgments. However, this was the case for the active conditions in both groups and feedback conditions. For the passive conditions, we observed increased time-interval judgments for the 300 ms group at both 300 and 900 ms feedback. This seems to suggest that the two training tasks might have been different and produced different effects for different levels of ADHD.

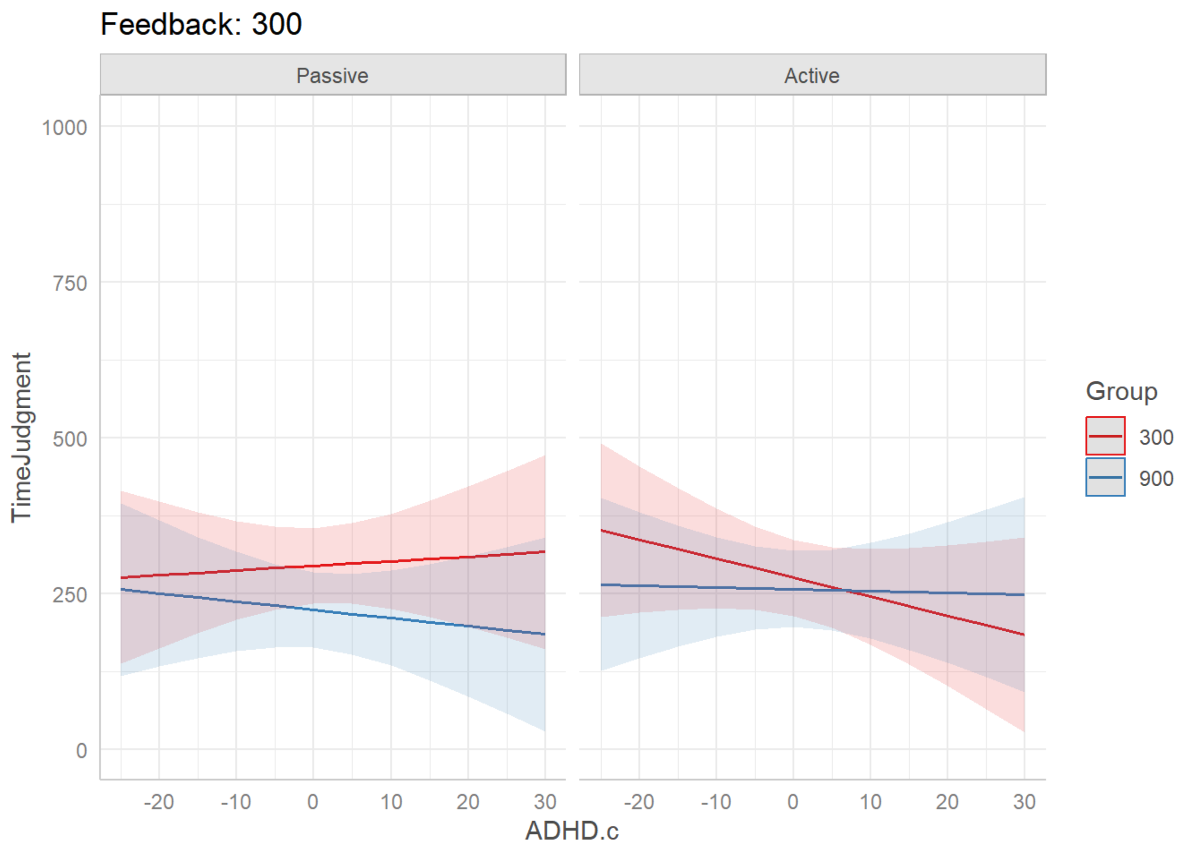


Plot 3: This plot shows the Time Judgment across different conditions (Passive and Active) for two different groups under the Feedback: 300 condition.

Generally, higher ADHD index values predicted shorter time-interval judgments. This trend was observed in the active conditions across both groups and feedback conditions. Conversely, in the passive conditions, we saw increased time-interval judgments for the 300 ms group at both 300 ms and 900 ms feedback. This suggests that the two training tasks might have produced different effects based on ADHD levels.

We then divided the ADHD values into three bins to better explore the differences across various ADHD levels. Interestingly, in the 300 ms feedback condition, participants with lower ADHD values showed no intentional binding effect; instead, they exhibited an opposite effect, mirroring the results observed in the 900 ms group. For higher ADHD values, the pattern changed, with the 300 ms group showing an intentional binding effect (Diff = 65.15 ms; $p < 0.001$). Conversely, the other group showed a negative difference between the passive and active conditions (Diff = -45.85 ms; $p < 0.001$). This suggests that the specific 300 ms training was effective only for participants with some levels of attentional disorders.

Similarly, we observed a difference between the two groups in the 900 ms feedback condition, but only for participants with higher ADHD levels. In this case, the training induced a reduction of the intentional binding effect.



Plot 9: This plot represents the relationship between ADHD scores (ADHD.c) and Time Judgment under different conditions (Passive and Active) and for different target interval groups (300 ms and 900 ms). The plot is divided into two panels based on the condition: Passive and Active.

Result Outcomes

Primary Outcome

We measured the primary outcome of the intentional binding effect between active and passive task and found a difference between the two tasks, with the active having larger temporal binding that the passive. We then tested whether group had a significant impact and showed intentional binding. We found that the 300ms group showed no intentional binding in the 300ms feedback condition in the active task. But in the 600ms feedback condition, the 300ms group and the 900ms group did show intentional binding. The 900ms feedback condition also showed the intentional binding effect in the 300ms and 900ms groups. So Intentional binding is present at the 600ms and 900ms feedback conditions, but not in the 300ms feedback condition.

We performed a 3-way ANOVA (mixed-model) and we found no 3-way interaction between the manipulations and dependant variable which is the Intentional Binding Index. However, when we measured the group effect, we found an interaction between the feedback condition and the group, showing there is a difference between the two groups in task condition, suggesting using that the 900ms group is learning.

Although not in the hypothesis, we followed a data driven approach, using a repeated measures analysis using the 600ms and 900ms feedback condition. If the subjects were learning in preliminary training, we would expect to see a change in the active task. The results do not show us if subjects are learning in the active or passive tasks. The results indicate there is no learning in the active condition for either of the two groups (300ms and 900ms). However, there is a trend in the two groups that learning effects the passive condition. We see a difference in the two groups in that the 900ms group is learning.

To conclude, the results are suggesting that there is no learning going in the active condition for either of the two groups. But there is a trend that the two groups are learning in the passive condition, or that learning does affect the passive condition. This means that there is no observable sense of agency at 300ms feedback, but there is sense of agency emerging at 600ms and 900ms feedback condition.

Secondary Outcome

The secondary shows the interaction between ADHD scores and the intentional binding effect across the feedback conditions. The study included a total of 60 participants (N=60), divided into two feedback conditions (300 ms and 900 ms), two training groups (Group 300 and Group 900), and two conditions (active and passive). Participants were further categorized into three ADHD levels (low, moderate, high).

For the 300 ms feedback condition, participants in Group 300 (passive condition) showed a mean time judgment of 280.45 ms (SD = 35.67 ms) for those with low ADHD, 270.32 ms (SD = 42.11 ms) for moderate ADHD, and 262.67 ms (SD = 37.33 ms) for high ADHD.

In the active condition for Group 300, participants with low ADHD had a mean time judgment of 310.45 ms (SD = 40.12 ms), moderate ADHD participants judged the interval at 305.12 ms (SD = 38.78 ms), and high ADHD participants at 300.67 ms (SD = 37.90 ms).

In the 900 ms feedback condition, participants in Group 900 (passive condition) with low ADHD showed a mean time judgment of 610.34 ms (SD = 78.25 ms), while those with moderate ADHD had a mean judgment of 580.12 ms (SD = 65.12 ms), and participants with high ADHD had a mean of 577.74 ms (SD = 322.26 ms).

In the active condition, participants with low ADHD judged the interval at 550.67 ms (SD = 58.12 ms), moderate ADHD participants at 540.22 ms (SD = 60.78 ms), and high ADHD participants at 530.34 ms (SD = 61.90 ms).

This shows a significant two-way interaction between group and condition was found for both the 300 ms feedback ($F(1, 1967.77) = 5.14$, $p = 0.023$) and the 900 ms feedback ($F(1, 1964.65) = 15.54$, $p < 0.001$).

In the 300 ms feedback condition, the mean difference between the passive and active conditions was 137.27 ms ($t(2120.60) = 12.26$, $p < 0.001$).

Additionally, a significant three-way interaction between group, condition, and ADHD level was observed in both the 300 ms feedback ($F(1, 1969.77) = 24.03$, $p < 0.001$) and the 900 ms feedback ($F(1, 2116.69) = 17.63$, $p < 0.001$).

The results show that participants higher on the ADHD index generally showed smaller time judgments in the active conditions across both feedback intervals, while passive conditions produced increased time judgments. In particular, the 300 ms feedback condition exhibited a stronger training effect for participants with higher ADHD levels, where the active condition led to significantly shorter perceived time intervals compared to the passive condition.

We performed statistical assumption checks, including normality tests, Levene's test, and Mauchly's test for sphericity. Where assumptions were violated, we applied corrective measures such as Welch’s ANOVA and Greenhouse-Geisser corrections to ensure the robustness and validity of the results.

Discussion

The primary aim of this study is threefold:

1. To evaluate whether a structured learning procedure can systematically alter the intentional binding effect in participants.
2. To compare the magnitude of the intentional binding effect between groups exposed to different temporal intervals during training (300 ms vs. 900 ms).
3. 3. To investigate the extent to which ADHD symptomatology modulates the intentional binding effect across different experimental conditions.

It was hypothesized that if the subjects learned from the training, in the actual experiment, the 300 ms group would experience larger intentional binding for the 300 ms time-interval task, and similarly, the 900 ms group would experience larger intentional binding for the 900 ms time-interval task. This expectation was based on the idea that participants would learn the timing between an active task (action-tone) and a passive task (tone-tone), thereby increasing their sense of agency.

The initial analysis did not align with the hypothesis, as no temporal shortening was observed in the 300 ms training group for the corresponding 300 ms active task. Notably, temporal shortening was identified in the 900 ms training group during the 600 ms and 900 ms feedback conditions. These findings contradict our expectations, as previous literature suggests that intentional binding should be apparent in both groups following training. However, upon closer examination of the specific methodologies employed, these results can be understood from an alternative perspective. Nonetheless, these results contribute to our continuous understanding of learning on the intentional binding effect. In this discussion, the potential meanings implications and of these findings will be explored.

The exploratory hypothesis posits that high ADHD symptomology (measured by the ADHD index) would serve as a cofounding factor in the experiment. To be specific, it was anticipated that participants with a high ADHD index would perceive time delays in both active and passive tasks as significantly shorter compared to individuals with low or no attention deficits.

Supported by research by Wenke & Haggard (2009), we speculate that as one makes a voluntary action, it seemingly slows down the “internal clock” as the brain allocates resources towards the focus of attention and starts predicting the action’s motor-sensory outcomes, resulting in a perceived temporal shortening, which is the intentional binding effect. So, we anticipated that higher rates of ADHD on the index would struggle to promptly allocate attentional resources to the correct action and stimuli in the experiment and be less effective at gauging the temporal duration on the initial learning procedures. Consequently, they would not develop a feeling of control through learning and not show the intentional binding effect.

When examined in a three-way interaction between training group, task condition, and the rate of self-reported ADHD symptomatology (ADHD index), a pattern was observed wherein high ADHD index scorers made smaller judgments on the time-delay in active conditions, alluding to the intentional binding effect. However, the results did not exactly align with our hypothesis, as in the passive conditions, a greater time-interval judgment was observed for both training groups. Therefore, if the learning trial did modulate the Intentional Binding effect, we would see contingencies following group allocation and feedback condition.

These findings suggest that those with high ADHD index scores exhibit distinct temporal processing capabilities during 300ms and 900ms training trials, potentially leading to differential task performance outcomes when compared to participants without ADHD symptomology. This disparity may result in the training exerting varying effects depending on the severity of ADHD symptoms, as indicated by the ADHD index. This interpretation aligns with the consensus that those with ADHD have difficulty perceiving small differences in time, especially in tasks that require quick judgments of brief time intervals, due to issues with attention and impulsiveness (Smith A, et al, 2002).

Discussing the science of ADHD is beyond the scope of this thesis, so a comprehensive explanation for these results cannot be provided. However, based on the temporal model for subjective time perception and the focus of attention previously stated, it may be that the "switch" in high ADHD symptomology brain changes too frequently during a 900ms training procedure, preventing the 900ms group from effectively gauging the sense of time passing.

It could be theorized that this occurs because for subjects to learn from the 900ms training, sustained attention from stimulus responses is required. This necessitates the effective allocation of cognitive resources to maintain attention for the entire 900ms timeframe - meaning to avoid mind-wandering, task-unrelated thoughts, mindlessness, or environmental distractions, which the ADHD afflicted mind is especially prone to (Nejati, V., & Yazdani, S., 2020). Additionally, participants with ADHD might make more impulsive and careless judgments on the time-slider, leading to increased errors in marking the correct time they truly judged and obscuring the results.

Further exploratory analysis divided ADHD values into three components to examine differences in ADHD levels. The initial hypothesis analysis showed no intentional binding in the 300ms feedback condition for the 300ms group. However, when observing the participants with a high ADHD index score, those in the 300ms training group did exhibit intentional binding in the 300ms feedback condition. This suggests that 300ms training induces IB but only in individuals with a high ADHD index score.

We can rationalise this finding in reference to the "Internal Clock Model", in that those with ADHD might feel a faster "pulse" or quicker changing of the "switch" that too fast to accumulate information in a 900ms training condition. But it might be a suitable time for the faster 300ms training condition, as this learning condition does not require sustaining focus of attention for so long. But it should be noted that the sample size for this cohort is insufficient to make definite conclusions, and this could be a direction for future investigation.

Similarities of Results

Differences in Experimental Method for Measuring Intentional Binding

Our study deviates from the conventional Libet Clock (LC) (Libet et al., 1983), method typically used to measure the Intentional Binding effect. In the LC experiment, participants observe a fast-moving clock hand and estimate the timing of an action and its effect compared to a control condition. This method consistently demonstrates Intentional Binding, where voluntary actions are perceived as occurring later (action binding) and effects are perceived as occurring earlier (effect binding). The LC method is highly robust and has been extensively validated in scientific studies (Tanaka et al., 2019).

In contrast, our experiment requires participants to estimate the interval between action and effect using a numerical slider ranging from 0 to 1200 ms, rather than observing a clock face. Participants make post-hoc judgments by producing a numerical estimation, a method that lacks the same level of scientific consensus and validation as the LC method (Siebertz & Jansen, 2022). These two methodologies consistently yield different results in the literature regarding temporal compression and are influenced by various factors; For instance, induced states linked to a loss of control, such as fear and anger (Christensen et al., 2019), have been shown to reduce IB in the LC-paradigm. Conversely, Wen et al. (2015) observed increased Intentional Binding with higher general arousal using the Interval Estimation (IE) method.

Based on the evidence, it is plausible to expect deviations from the norm in the study's results due to the use of the interval estimation method. This approach, which requires participants to retrospectively estimate time intervals and input them as numerical values on a slider, may introduce errors related to the conversion of time perceptions into numerical representations, potentially compromising data reliability.

Furthermore, it is essential to consider uncontrolled variables, such as individual differences in working memory, sustained attention or predisposition to dyscalculia (Üstün, S., et al, 2021) which may make it difficult for a person to convert time into a numerical value mentally. These cognitive functions can be also influenced by factors beyond attentional deficits, such as depression (Scott, N.J., 2022) which have not been controlled for in the experiment. Given these individual differences, some participants may exhibit greater accuracy in estimating shorter time intervals, while others may perform better with longer intervals, irrespective of additional confounding factors like emotional state and depression.

To improve the study, researchers might consider employing the Libet Clock method or alternative tools such as Interval Reproduction (IR) method, in which participants press a button for the duration of the interval between two events (Humphreys & Buehner, 2010). The use of Interval Reproduction method could produce different outcomes, especially for the 300ms group and 300ms feedback condition, where the current study did not observe the expected temporal binding. This auditory-based method may offer more intuitive measurements of interval timing, enabling participants to recreate their sense of time duration without converting it into numerical values. This approach could potentially reveal the intentional binding effect overlooked in the current study.

However, the interval reproduction method is usually used to measure the action-effect interval in experiments where each trial time-duration is randomized, whereas this study aims to assess Intentional Binding for constant and predictably varying action-effect intervals. Consequently, a hybrid of the interval reproduction method and this study's design framework might be a promising target for future investigation.

Similarities in Results for Intentional Binding

Our findings contradict the current consensus in the literature on the intentional binding paradigm, which suggests that intentional binding should be observed in the 300ms feedback condition for voluntary tasks. Prior research indicates that the optimal time-window for intentional binding is between 200 and 300 ms (Ruess, 2017).

However, this can be explained, as Ruess (2017) utilized the classic Libet Clock (LC) method, which involves a visual display of an analog clock with a continuously revolving hand as a reference for participants' time estimates. Given the evidence that the Libet Clock (LC) method and the Interval Estimation (IE) method can produce different IB effects, our findings diverging from the broader consensus on intentional binding is not necessarily problematic. It can be argued that these different methodologies measure distinct aspects of the intentional binding effect, suggesting the IB effect might have multiple underlying components.

Our results are consistent with the findings of Nolden et al. (2012), which employed the method of constant stimulus to study IB. Although our study did not use the method of constant stimulus, we observed a similar pattern: Nolden et al. (2012) found no IB effect at 250ms in either auditory or visual tasks but did observe the IB effect at 600ms. This supports the notion in some of the literature that depending on methodology the intentional binding effect may be more pronounced with longer time estimates rather than shorter ones.

Interpretation

Limitations and Strengths

A major limitation of this study was the inclusion of the passive condition in the training protocols for both the 300ms and 900ms groups. Exclusive training in the active condition would have ensured that any observed intentional binding effects were directly attributable to intentional actions. However, the addition of the passive condition introduces the risk of cross-condition contamination, where participants might have developed expectations about the time delays during passive training that influenced their responses in the active condition. This contamination complicates the interpretation of the results, particularly in the 300ms group, where the lack of an intentional binding effect could be due to the inability to isolate the learning effects between the active and passive conditions.

This potential cross-contamination complicates the interpretation of the results, particularly in the 300ms group, where the absence of the intentional binding effect might be partly attributed to the inability to isolate the learning from the active condition alone. In other words, the dual learning process may have prevented participants in the 300ms group from experiencing a significant intentional binding effect, possibly because they recognized that the time delays were consistent across conditions. Consequently, the passive conditions training inclusion limits our understanding on the temporal binding effect as we cannot definitively attribute the results solely to active learning processes or passive learning processes.

Another significant limitation of this study was the absence of a baseline measurement for intentional binding. Establishing a baseline before any training or exposure to specific time delays (e.g., 300ms or 900ms) would allow for an assessment of participants' initial intentional binding effect without prior conditioning. This would involve having participants perform the task without any exposure to time-delays to determine the natural strength of their sense of agency and intentional binding.

Instead, this study proceeded directly to the learning phase in both active and passive conditions, and this approach lacks a crucial comparison point, making it difficult to determine whether the learning process genuinely modulated the intentional binding effect. Although the passive tasks were intended to control for this, the fact that participants also received training in the passive condition undermines the reliability of this as a control. A more robust experimental design would have included pre- and post-training measurements of intentional binding per participant to provide clearer evidence of any changes attributable to the learning process.

The external validity of this study is supported using a diverse sampling pool, with a calculated sample size of 60 participants deemed mathematically adequate. However, there are contextual limitations due to the experiment being conducted online rather than in a controlled laboratory environment. The naturalistic online setting introduces potential for environmental distractions, variability, and technical issues, which may impact the study's legitimacy.

Study Implications

The study found that participants with a high ADHD index score were able to learn in the faster 300ms condition but struggled in the 900ms condition. This could be due to their inattentiveness during longer time intervals, while shorter intervals seem to suit them better.

To explore this further, researchers could conduct a similar experiment to measure the intentional binding effect at shorter time delays in participants diagnosed with ADHD, compared to neurotypical controls. It would be valuable to examine whether ADHD participants are indeed learning at short intervals and whether they exhibit the intentional binding effect. Additionally, investigating the potential correlation between ADHD severity and the strength of the intentional binding effect at shorter intervals could offer useful insights. This line of inquiry could inform future educational research, particularly in developing teaching methods for individuals with ADHD and specific learning difficulties.

A second avenue for future research is to compare different methodologies used to measure the intentional binding effect. The scientific literature indicates that various methodologies can yield contrasting evidence regarding intentional binding. The method used in this study is less robust than others that have been tried and tested.

It would be interesting to see if the findings could be replicated using a more established method, such as the interval reproduction method. This approach might be preferable, as it could minimize participants' difficulty in converting time into numerical values or making careless mistakes on a slider. Instead, it would rely on participants' instinctual sense of rhythm and musical timing to demonstrate the intentional binding effect.

Conclusion

In conclusion, this study provides evidence that learning influences the intentional binding (IB) effect, suggesting that the sense of agency (SoA) is shaped by experience. Participants trained with a 900ms delay showed a significant increase in IB, indicating that learning specific time intervals enhances the perception of control over action-outcome sequences.

We confirmed the IB effect by observing a clear difference between active and passive tasks, with active tasks showing stronger binding. While the 300ms group did not exhibit IB in the 300ms condition, both the 300ms and 900ms groups demonstrated IB in the 600ms condition. Similarly, both groups showed IB in the 900ms feedback condition. Although no three-way interaction was found, the 900ms group showed evidence of learning.

Developing a sense of agency is crucial for understanding how our actions affect the world. While the question of whether learning can fully modulate IB remains unresolved, this research contributes to advancing human-computer interaction studies advancing neuroprosthetics, skill mastery, and expertise.

Though the link between learning and IB is still under-researched, this study offers valuable insights in this domain. It also highlights potential areas for future research, particularly regarding ADHD's impact on IB and attention, which could improve our understanding of neurodivergent learning and how this related to the SoA. Philosophically, the findings prompt questions about the nature of agency—how it develops through learning, and whether it can be enhanced indefinitely, adding depth to discussions about neuroplasticity, human cognition and adaptation and self-perception.

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Detailed Experimental Procedure:

Information Sheet

DEPARTMENT OF PSYCHOLOGICAL SCIENCES
BIRKBECK UNIVERSITY OF LONDON
INFORMATION SHEET for: "Can Intentional Binding travel through time"?

Before you decide to take part in this study, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully and discuss it with others if you wish. A member of the research team can be contacted if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

This research project looks at if the intentional binding effects can be manipulated through learning. This study will be completed by 1st August 2024.

You have been chosen to participate in this study as you are 18+ years old.

In this study, you will be asked to sit Infront of a computer screen for less than an hour with breaks in-between. This study will take place online. Through the experiment, you will be asked to judge the elapsed time between an event (either your own action or a tone) and another event (a tone).

Describe any possible disadvantages/risks and benefits of taking part

The results of this project will be written up for an MSc Psychology Dissertation. All participant information collected will be anonymous and remain confidential.

You have the right to withdraw participation at any point up until the point that the anonymised data can no longer be identified.

The project has received ethical approval from the School of Science Research Ethics Committee, Birkbeck, University of London

Researcher: Ffion Reed. freed02@student.bbk.ac.uk
PI: Raffaele Tucciarelli. R.tucciarelli@bbk.ac.uk Primary investigator contact details: Dr Raffaele Tucciarelli, r.tucciarelli@bbk.ac.uk

For information about Birkbeck's data protection policy please visit: http://www.bbk.ac.uk/about-us/policies/privacy#7

If you have concerns about this study, please contact the School's Ethics Officer at: ethics@psychology.bbk.ac.uk

School Research Officer School of Science, Department of Psychological Sciences Birkbeck, University of London London WC1E 7HX

You also have the right to submit a complaint to the Information Commissioner's Office https://ico.org.uk/

Consent Form

DEPARTMENT OF PSYCHOLOGICAL SCIENCES
BIRKBECK UNIVERSITY OF LONDON
CONSENT FORM for: "Can Intentional Binding travel through time"?

I have had the details of the study explained to me and willingly consent to take part. My questions have been answered to my satisfaction and I understand that I may ask further questions at any time.

I understand that I will remain anonymous and that all the information given will be used for this study only.

I understand that I may withdraw my consent for the study at any time without giving any reason and to decline to answer particular questions. Furthermore I understand that I will be able to withdraw my data up to the point that the anonymised data can no longer be identified.

I understand that audio/video recordings will be made and identified with a unique code, but after the results of the experiment have been collected, these recordings will be destroyed. The recordings will only be used for the purpose of the research project.

I understand that all information given will be kept confidential and only the immediate researchers will have access to the data collected. The data will only be held for a short time for the purpose of this research project and destroyed after we have calculated the results.

I understand how the results of the study will be used; The results will be written up for a dissertation thesis.

I confirm that I am over 18 years of age

I Agree

I have read and understood the above and hereby give my consent to take part in this experiment in full knowledge that data is being recorded.

ADHD Symptomatology Questionnaire

Demographic Questions.

How old are you?

- 18-25
- 26-30
- 31-36
- 37-45
- 46-50
- 51+
- Prefer not to say

Which gender do you identify with?

- Male
- Female
- Non Binary
- Transgender
- Prefer not to say
- Other - please specify:

What is your Ethnicity? (If you do not wish to answer, please write 'prefer not to say')

Have you been diagnosed with ADHD?

- Yes
- No
- Prefer not to say

Next

Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist

*This is not a diagnostic self-report, participants will not be diagnosed with ADHD if they complete the questionnaire. This is only PART A of further tests which involves specialists and Psychiatrists.

The Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist was developed in conjunction with the World Health Organization (WHO), and the Workgroup on Adult ADHD that included the following team of psychiatrists and researchers:

• Lenard Adler, MD Associate Professor of Psychiatry and Neurology New York University Medical School

• Ronald C. Kessler, PhD Professor, Department of Health Care Policy Harvard Medical School

• Thomas Spencer, MD Associate Professor of Psychiatry Harvard Medical School

References:

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Please answer the questions below, rating yourself on each of the criteria shown using the scale. Answer with what best describes how you have felt and conducted yourself over the past 6 months.

How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?

Never / Rarely / Sometimes / Often / Very Often

How often do you have difficulty getting things in order when you have to do a task that requires organization?

Never / Rarely / Sometimes / Often / Very Often

How often do you have problems remembering appointments or obligations?

Never / Rarely / Sometimes / Often / Very Often

When you have a task that requires a lot of thought, how often do you avoid or delay getting started?

Never / Rarely / Sometimes / Often / Very Often

How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?

Never / Rarely / Sometimes / Often / Very Often

How often do you feel overly active and compelled to do things, like you were driven by a motor?

Never / Rarely / Sometimes / Often / Very Often

How often do you make careless mistakes when you have to work on a boring or difficult project?

Never / Rarely / Sometimes / Often / Very Often

How often do you have difficulty keeping your attention when you are doing boring or repetitive work?

Never / Rarely / Sometimes / Often / Very Often

How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?

Never / Rarely / Sometimes / Often / Very Often

How often do you misplace or have difficulty finding things at home or at work?

Never / Rarely / Sometimes / Often / Very Often

How often are you distracted by activity or noise around you?

Never / Rarely / Sometimes / Often / Very Often

How often do you leave your seat in meetings or other situations in which you are expected to remain seated?

Never / Rarely / Sometimes / Often / Very Often

How often do you feel restless or fidgety?

Never / Rarely / Sometimes / Often / Very Often

How often do you have difficulty unwinding and relaxing when you have time to yourself?

Never / Rarely / Sometimes / Often / Very Often

How often do you find yourself talking too much when you are in social situations?

Never / Rarely / Sometimes / Often / Very Often

When you’re in a conversation, how often do you find yourself finishing the sentences of the people you are talking to, before they can finish them themselves?

Never / Rarely / Sometimes / Often / Very Often

How often do you have difficulty waiting your turn in situations when turn taking is required?

Never / Rarely / Sometimes / Often / Very Often

How often do you interrupt others when they are busy?

Never / Rarely / Sometimes / Often / Very Often