Nonverbal Syllogisms as a Test for Fluid Intelligence

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Abstract

Syllogisms have a long history of being used to test fluid intelligence and its aspects. Nonverbal versions were proposed as a preferable alternative to traditional verbal syllogisms, which have well recorded disadvantages. Two experiments were performed to test the validity of nonverbal syllogisms as measures of the fluid intelligence aspects, working memory and spatial reasoning, respectively. Participants carried out a time-restricted version of Raven's Advanced Progressive Matrices (RAPM), and a 64-channel EEG recording registered their brain activity as they evaluated nonverbal syllogisms. The nonverbal syllogisms were constructed differently for each experiment, specifically as a working memory test in the first experiment and as a spatial reasoning test in the second experiment. Participants' performance in the RAPM and in evaluating nonverbal syllogisms was shown to be correlated in both experiments. Furthermore, the presence of the frontal midline theta rhythm, which has been associated with fluid intelligence, was also noted in both experiments. Additionally, the theta activity along the frontal midline increased with the difficulty of the nonverbal syllogisms that participants had to evaluate. These results replicate the findings of prior studies on the frontal midline theta rhythm and further support the validity of nonverbal syllogisms as versatile and flexible measures of fluid intelligence and its aspects.

Keywords: Syllogisms, fluid intelligence, EEG, Raven Advanced Progressive Matrices, frontal midline theta rhythm, working memory, spatial reasoning

Nonverbal syllogisms as a test for fluid intelligence

Human intelligence has been a major field of research and testing within psychology practically since the moment it could be first formally labelled as a scientific discipline (Wilhelm & Schroeders, 1988). One of the most prevalent theories was put forward by Cattell (1963), who differentiated between crystallized and fluid intelligence. Crystallized intelligence is a result of learned knowledge and internalized information gained from study and past experiences, while fluid intelligence details the ability to perceive, process, and manipulate novel stimuli (Cattell, 1963). The specifics of fluid intelligence have long been debated and associated with numerous different aspects, with some examples being types of reasoning, such as inductive or analytical, pattern recognition, manipulation of information within working memory, or spatial ability (Haavisto & Lehto, 2005; Kyllonen & Christal, 1990).

Of these two distinct types of intelligence, fluid intelligence is of great interest for any activity requiring individuals to evaluate and act upon incoming information. Such capability is important for the more abstract, such as evaluating scientific information, to the more practical, like retaining and acting upon spatial relations (Unsworth et al., 2014). For these and similar activities, it is important to identify whether and to what extent individuals possess relevant aspects of fluid intelligence. While past claims that fluid intelligence is immutable (Jensen, 1969) have been disputed in more recent times (Sternberg, 2008), it is still a valuable attribute to establish for professional pursuits or as a baseline from which to improve.

As fluid intelligence is quite multi-faceted and many properties have been associated with it, attempting to measure it in its entirety can be problematic. Instead, methods for measuring fluid intelligence primarily focus on testing a specific, relevant aspect. Particularly working memory and spatial ability are properties that are commonly measured, as prior research has shown that correlations between measures of these properties and fluid intelligence exist (Kent, 2017; Lohman, 1996). Prominent examples of methods to test aspects of fluid intelligence include psychometric tests employing syllogisms, IQ tests like the Raven Advanced Progressive Matrices (RAPM), or physiologically via electroencephalography (EEG). Syllogisms especially have a long history in the testing of fluid intelligence, but they also have major and well-recorded issues, largely due to their verbal nature (Evans et al., 1983; Ortiz et al., 2012). A potential solution to these problems could be replacing the verbal components of traditional syllogisms with nonverbal alternatives, essentially creating nonverbal syllogisms. Nonverbal syllogisms could thereby retain the versatility of verbal syllogisms without the issues that have been noted in their usage. This research attempted to validate nonverbal syllogisms' potential as a flexible and versatile measure of fluid intelligence and further explored their usage in testing specific aspects of fluid intelligence.

Prior testing of fluid intelligence

Testing via syllogistic reasoning has successfully allowed systematic explorations of fluid reasoning (Frandsen & Holder, 1969; Robison & Unsworth, 2017; Spearman, 1961). Syllogisms present individuals with several premises, essentially given statements, and then ask them to evaluate, based on these premises, whether following conclusions are correct or incorrect. An example of a correct verbal syllogism is: “All men are human; all humans are mortal; therefore, all men are mortal.” (Merriam-Webster, n.d.). While syllogisms have been successfully used in the testing of fluid intelligence, they have several significant issues, largely related to the verbal nature of syllogisms. Evans et al. (1983) performed extensive experimentation to test reports of a tendency to evaluate syllogisms based on the believability of the given statements, which indeed found the existence of such a belief bias. Furthermore, this was not the only study that supported this phenomenon (Klauer et al., 2000; Newstead et al., 1992; Tsujii & Watanabe, 2009), making syllogisms a problematic tool for the measurement of fluid intelligence. This is further complicated due to the issues that can emerge in verbal psychological testing due to individual differences in language comprehension and cultural backgrounds (Ortiz et al., 2012).

Many different measures for testing fluid intelligence exist, however, the RAPM is one of the most widespread methods to test fluid intelligence. Specifically, the RAPM has proven successful in measuring properties such as analytical and abstract reasoning (Raven et al., 1998). What distinguishes it from other tests of fluid intelligence is its largely non-verbal nature, allowing scores that are less influenced by the participants linguistic abilities and knowledge. Individuals taking the RAPM test will be given multiple geometric designs, with one space intentionally left blank (Raven et al., 1998). The test taker must then identify which of the potential options correctly completes the pattern that these given figures form for as many patterns as they can in the time they are given. Once the participant finishes all patterns or the time given runs out, it will be possible to tally up all the correct answers and compare them to others (Raven et al., 1998). There are different variations to the RAPM, but its methodology has extensive evidence that supports its ability to measure fluid intelligence (Carpenter et al., 1990; Raven, 2000).

Beyond just these behaviourally focused methods, neuroimaging studies have found success in exploring fluid intelligence by measuring bodily responses via methods such as EEG or functional magnetic resonance imaging (fMRI) (Fox & Raichle, 2007; Paszkiel, 2020; Perfetti et al., 2009; Prabhakaran et al., 1997). Both methods noninvasively measure brain activity and their usage in experiments found distinct brain activity as individuals engage with tasks demanding fluid intelligence. Ishihara and Yoshii (1972) were the first to explicitly call attention to increased activity in the theta band, the frequency band which ranges from four to eight Hz, along midline of the frontal brain regions, which they labeled the frontal midline theta rhythm. The participants in their research engaged with fifteen established tests of fluid intelligence, including tasks for mathematical calculation and geometric reasoning, which consistently produced increased theta activity along the frontal midline as long as participants remained focused on the tasks (Ishihara & Yoshii, 1972). Further research, such as the study by Klimesch et al. (1996), who employed a word recognition task, found that beyond the existence of a link between fluid intelligence and the frontal midline theta rhythm, said activity also increases corresponding to the difficulty of the given task. These trends of frontal midline theta activity related to fluid intelligence have consistently been demonstrated in multiple experiments, employing varied methods such as Sternberg tasks, syllogisms, or spatial working memory tasks (Jensen & Tesche, 2002; Maurer et al., 2015; Qiu et al., 2009; Roberts et al., 2013).

Nonverbal syllogisms

Prior concerns noted with traditional verbal syllogisms motivated the creation of nonverbal alternatives, which eliminate the potential influence of language, culture, and background on resulting data. Subject of continuous unpublished research at the University of Twente suggests the viability of nonverbal syllogisms as a measure of fluid intelligence, as this type of syllogism retains the structure and reasoning processes of verbal syllogisms but replaces all verbal components with visual ones. At their core, premises in verbal syllogisms establish relations between items, and conclusions must be evaluated based on whether they adhere to these relations. The information given explicitly by verbal syllogisms to facilitate this process can instead be communicated implicitly in nonverbal syllogisms, with the geometric figures placed in specific sequences.

For instance, take the verbal syllogism “x is to the left of y; y is to the left of z; therefore, x is to the left of z.” This can be translated into a nonverbal form by displaying a circle left of a square for the first premise, a square left to a triangle for the second premise and a circle in front of a triangle for the conclusion. The spatial relations of the items are the same as with the verbal syllogism, but no more verbal components can negatively influence the reasoning processes taking place.

While this demonstrates how nonverbal syllogisms might serve to facilitate the same reasoning processes as verbal syllogisms, nonverbal syllogisms used in this study were not structured in the same fashion. The basic concept of premises and conclusions remained the same as the example and premises depicted relations between two geometric figures, but conclusions were instead formed of a sequence of four figures. Further, participants had to use the premises to check whether the spatial relations were violated in the conclusion to evaluate whether it was correct or incorrect. Specific descriptions of the nonverbal syllogisms are given below.

Current research

The central problem that the current study was concerned with was that while syllogistic reasoning is frequently used to measure fluid intelligence, there are several problems that arise due to the traditionally verbal nature of syllogisms, which have been previously noted but not yet resolved. Nonverbal versions of syllogisms may serve as a potential solution to these issues, since they remove verbal components and as such avoid the drawbacks arising from verbal fluid intelligence testing. This research sought to validate nonverbal syllogisms as potential measures for testing fluid intelligence via its associated aspects, working memory and spatial ability. For that purpose, two experiments were performed, which were structured in the same fashion. Participants would first complete the RAPM, then solve nonverbal syllogisms while their brain activity was recorded via EEG. The major difference between the two experiments was how the nonverbal syllogisms were constructed, as they would consequently test different properties.

The first experiment employed nonverbal syllogisms that were constructed in the form of a memory task. Participants were required to fully memorize the given premises to evaluate the following conclusions, thereby allowing exploration of the previously reported trends that this results in theta activity and that such activity increases on account of more difficult versions of the task (Ishihara & Yoshii, 1972; Jensen & Tesche, 2002; Klimesch et al., 1996; Maurer et al., 2015; Qiu et al., 2009; Roberts et al., 2013). Replicating these effects would imply nonverbal syllogisms are a viable option for testing working memory. In the second experiment, nonverbal syllogisms were designed to demand spatial reasoning on top of memorization, which has not been explored via EEG to the same extent as working memory. This was done to shed further light on the neural elements of spatial ability and demonstrate the viability of nonverbal syllogisms in testing another property of fluid intelligence.

The EEG data resulting from these experiments were analysed with time-frequency (TF) analyses to be able to extract activity in the theta band over time. This approach was inspired by the study on motor imagery and execution by Van der Lubbe et al. (2021), which employed a comparable methodology involving TF analyses with Morlet wavelets. Similarly, their mass univariate approach for statistical analysis was also replicated, albeit with some adaption based on aspects of this research, which they themselves adapted from Groppe et al. (2011). Focus was primarily placed upon the influence of difficulty of nonverbal syllogisms on theta activity occurring at the frontal midline, with a secondary focus on establishing which hemisphere appears more involved in fluid intelligence processes. Lastly, conditional differences in behavioural and electrophysiological data were explored with linear mixed models, as it has been reported that this method has advantages over more traditional repeated measures methods (Krueger & Tian, 2004; Schielzeth et al., 2020).

The following general predictions were based on prior studies' findings into fluid intelligence and were central in demonstrating the viability of nonverbal syllogisms as a fluid intelligence measure. As these were applicable for both working memory and spatial reasoning, no experiment-specific hypotheses or predictions were generated, rather, it was tested whether these general predictions were supported for both experiments separately. As nonverbal syllogisms are expected to measure fluid intelligence, much like the RAPM, it was expected that there would be a correlation between participants' RAPM scores and their sensitivity in evaluating nonverbal syllogisms. Furthermore, as the higher difficulties of the nonverbal syllogisms place higher demands on the participants, it was expected that participants' respective behavioural measures of sensitivity in correctly evaluating nonverbal syllogisms and their reaction time would decrease as the difficulty increased. Similarly, it was assumed that theta activity would increase as difficulty increased to reflect the increased workload for the participant. The activity was predicted to be the greatest along the frontal midline due to overlaying the prefrontal cortex, which has been associated with fluid intelligent operations. Lastly, it was considered likely that participants' sensitivity in correctly evaluating nonverbal syllogisms might be correlated with the mean theta activity generated as participants work on solving nonverbal syllogisms.

Experiment 1: Using nonverbal syllogisms to test working memory

The first experiment focused on whether it was possible to use nonverbal syllogisms to replicate the trends regarding theta activity that were noted in prior studies (Ishihara & Yoshii, 1972; Jensen & Tesche, 2002; Klimesch et al., 1996; Maurer et al.,2015; Qiu et al., 2009; Roberts et al., 2013). The aspect of fluid intelligence investigated in this first experiment was working memory, as multiple publications argue that working memory is closely related to fluid intelligence (Conway et al., 2002, Engle et al., 1999; Kane et al., 2005). Furthermore, it is well documented that individuals performing working memory tasks exhibit noticeable theta activity along the frontal midline, increasing activity depending on the task's difficulty. For instance, Maurer et al. (2015) employed EEG to test frontal midline activity while participants faced modified Sternberg tasks with either low or high working memory loads. Their experiment demonstrated that theta activity at frontal regions noticeably increased with the task difficulty and that the increase negatively correlated with participants' performance (Maurer et al., 2015). While the Sternberg task is one of the most prominent ways to test working memory, and as such fluid intelligence, the trends in frontal midline theta activity have also been demonstrated with other methods (Ishihara & Yoshii, 1972; Klimesch et al., 1996; Sauseng et al., 2010). Working memory is therefore a good aspect of fluid intelligence to test with nonverbal syllogisms, as the trends in behavioural and physiological data can be compared to these previous studies. Observing these effects would serve to validate nonverbal syllogisms as a functional measure of a critical aspect associated with fluid intelligence.

Consequently, nonverbal syllogisms were constructed in a way that would primarily burden working memory, as participants needed to fully memorize the positions of the differently coloured geometric figures to evaluate the following conclusions. Furthermore, the conclusion was only shown for a limited time and hid before participants were able to answer. This was done to ensure there was a period wherein the participant was primarily focused on solving the syllogisms, as even just the planning or imagining of movement can generate activity confounding the desired data (Ketenci & Kayikcioglu, 2019; Van der Lubbe et al., 2021).

Method

Participants

In total, twenty-six individuals participated in the first experiment. Four participants had to be excluded entirely due to technical complications with the equipment. Furthermore, the RAPM score for one participant could not be properly recorded, so their data was excluded for any analyses that involved this variable. All participants were recruited from the Test Subject Pool SONA, a platform maintained by the University of Twente. Of the twenty-two participants that qualified for analysis (M_{age} = 20.4 years, *SD* = 2.0; 12 German, 7 Dutch, 3 Other; 14 female, 7 male, 1 non-binary; 21 right-handed, 1 ambidextrous assessed with Annett's Handedness Inventory, Annett, 1970), eighteen participants reported normal or corrected-to-normal vision, indicated they had no histories of cognitive disorders, physical injuries or impairments, drug or alcohol addictions, and had used no medication prior to the experiment. The remaining three participants did indicate histories of cognitive disorders or the use of medicine before the experiment session, however in later inspection it was noticed that their data were highly comparable to those of the other nineteen participants, and as such it was considered acceptable to include these participants in the subsequent analyses. This experiment received ethical approval (Requestnr.: 211272) from the BMS Ethics Committee of the University of Twente.

Stimuli and task

This experiment employed a repeated measures design. Participants had to complete two major tasks, which each utilized their own materials and setups. The first part involved a Qualtrics survey that participants had to complete before the EEG could be set up. This survey contained demographic questions, colour blindness and visual acuity tests, a scale to determine handedness, an EEG questionnaire, and lastly the RAPM. In the second part of the experiment participants would have their brain activity recorded via EEG, while they worked on solving nonverbal syllogisms. Both tasks will be described in greater detail below.

Raven advanced progressive matrices

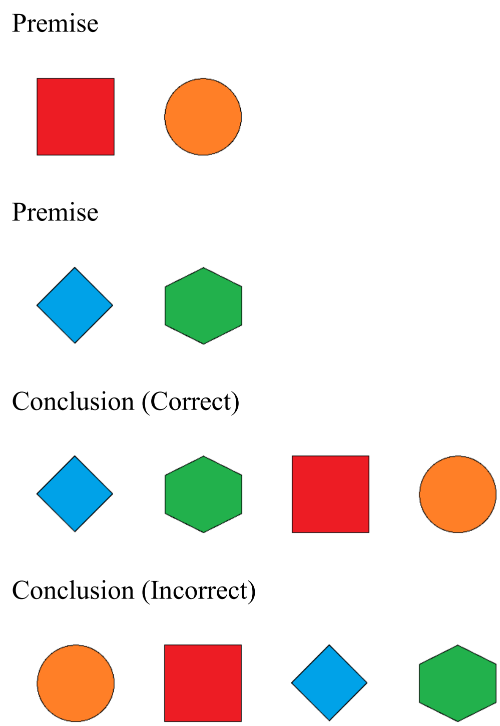
The RAPM version used was Set II containing 36 questions (Raven et al., 1998). Originally printed on paperback, all questions and their potential answer options were scanned and placed in a Qualtrics survey. In the survey, each question was presented as a multiple choice, while the participant had to select the option that would best complete the pattern. Lastly, due to the time-intensive nature of EEG experiment, participants only had 20 minutes to answer as many questions as possible, as previous research noted that there was a high correlation between the results of unrestricted and time restricted RAPM tests (Hamel & Schmittmann, 2006).

Nonverbal syllogisms

The experiment used the Presentation software (version 23.0) created by Neurobehavioural Systems Inc. to program and display the nonverbal syllogisms. The difficulty of the nonverbal syllogisms was manipulated by presenting either two (easy), three (medium), or four (hard) premises, which would then be followed by ten conclusions, with their order being fully randomized, that had to be evaluated by the participant. In these subsequent conclusions, participants had to check whether 1) the geometric figures shown in the premises appeared directly next to one another and 2) if the figures were arranged in the same order as given. If the figures given by the premises did appear directly next to one another, and they were in the order presented by the premises, then the conclusion was correct. If the geometric figures shown in premises appeared in the reversed order in a conclusion, it was incorrect. In any other situation, the conclusion was correct.

Figure 1

Example of a set of premises and conclusions used in the first experiment



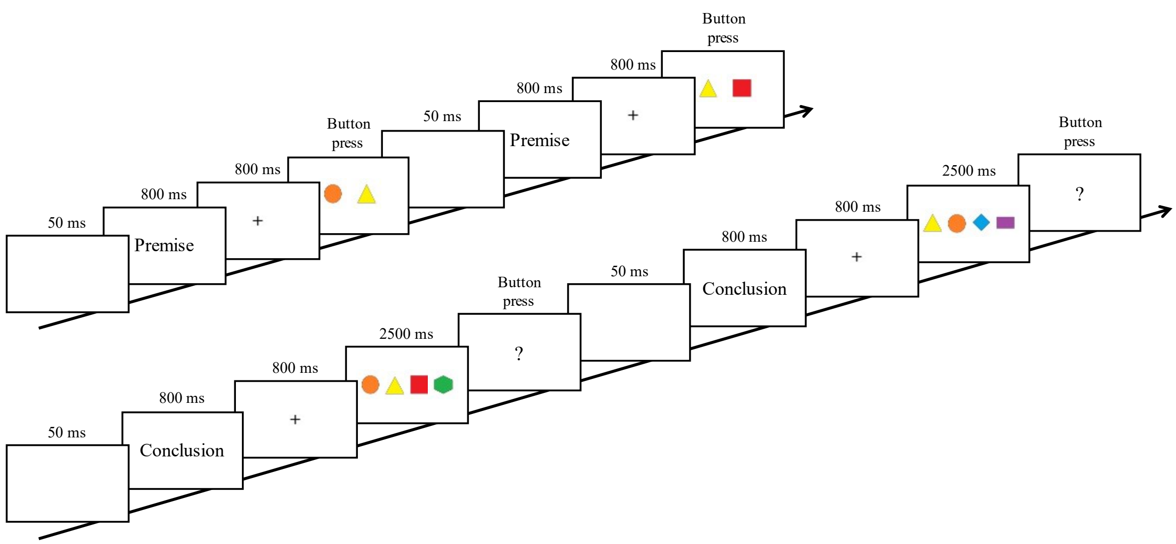
Note. Example of a nonverbal syllogism employed in the first experiment, showing two premises (above) used to evaluate two conclusions (below). The premises can be verbally described as “red square must be in front of orange circle if both appear next to each other” and “blue rhombus must be in front of green hexagon if both appear next to each other.” In the first conclusion all the figures are in the order given by the premises, making it correct, while in the second conclusion the orange circle appears in front of the red square, making it incorrect.

In total, participants had to memorize 30 sets of premises and judge a total of 300 conclusions, with 100 trials per difficulty. These 100 trials were further divided into two blocks of 50 trials each, so participants were not presented with all trials for one difficulty at once. The order of these blocks was counterbalanced across the sample (see Appendix D). Every block had five sets of different premises and conclusions to be memorized and evaluated, respectively.

At the start of a block, the participant was informed how many premises they would receive. Following that, premises were presented one at a time, without a time limit for attempting to memorize them. Rather, the participant chose when to advance to the next premise by pressing the up arrow key. Additionally, each premise was shown to the participant twice, in the same order, to give them two separate chances to fully memorize them. Once they determined they had sufficiently memorized which pairs of geometric figures appeared in the premise and their order, the participant advanced the page and was shown one conclusion at a time. Said conclusions were shown for a limited time during which participants were unable to respond. Once 2,500 ms had elapsed, the conclusion was hidden and the participant was able to indicate whether they believed the conclusion to be correct, by pressing the left arrow key, or incorrect, by pressing the right arrow key. There was no time limit for giving a response, but it was advised to answer as quickly and confidently as the participant was able once the screen changed, rather than continuously revising their answer. Once participants gave their response, there would be a brief time before the next conclusion was shown and they would have to repeat the answering process. This continued until ten conclusions were judged, at which point the next set of premises and conclusions was presented. After the participant advanced through every set in a block, there was a short pause before the participant started on the next block of the order.

Figure 2

Stimuli timeline for the first experiment



Note. Stimuli timeline for the presentation of a set of premises (above) and conclusions (below) like those used in the first experiment. Text above the images corresponds to how long a specific screen would be shown. A set of trials began by presenting participants with premises, which were viewable until the participant decided to advance the screen and repeated once. After 1,650 ms passed, participants saw their first conclusion. Conclusions were presented one at a time and replaced with a white screen with a question mark after participants had 2,500 ms to view them, at which point they could give a response. Participants were only shown the next conclusion 1,650 ms after they gave a response.

Procedure

The experiment was performed entirely in a laboratory setting, in a room specifically designed for EEG research. As this experiment occurred during the COVID-19 pandemic, preventive measures, such as wearing face masks and disposable gloves, were taken to minimize risks to both the researcher and participant.

The session began by acquiring the participant's informed consent. Once informed consent was given, the first part of the experiment began, which had participants fill out an extensive Qualtrics survey on a laptop, which asked for demographic information, tested for colour blindness, visual acuity, and handedness, asked several questions regarding participant physical and mental state. The last part of the survey was the RAPM. Once the 20 minutes participants were given elapsed, the survey ended, and the second part of the experiment began.

For the second part of the experiment participants were placed 70 cm away from a 22'' LED screen refreshing at a rate of 60 Hz connected to the device that featured the nonverbal syllogisms. EEG specific data was recorded using hard- and software developed by Brain Products (n.d.). 65 Electrodes were attached to the participant's head according to the standard 10-20 system, with the electrode at Fpz being used as ground, while the electrode at TP8 served as the online reference electrode. The electrodes' impedances were kept below 10 kΩ. Aside from these electrodes, horizontal and vertical EOG (hEOG and vEOG), were applied around the participant's eyes and forehead to record eye movement related activity. BrainVision Recorder was used to record participant's EEG data at a sample rate of 1000 Hz after the signals were amplified by an actiCHAMP amplifier.

Participants received instructions on how to evaluate nonverbal syllogisms, both written and spoken (see Appendix E), while the EEG was set up and had any questions answered before the start of the experiment. Once the participant had no more questions, they worked through a practice block. The practice block reiterated the initial instructions and ran the participant through a set of 3 premises and conclusions. Based on the number of misses and false alarms in this practice block, participants would receive additional instructions to confirm they fully understood nonverbal syllogisms and how to evaluate them properly.

Once this was ensured, participants started the actual experiment. Participants were able to take a short break whenever they completed a set of premises and conclusions and longer breaks took place whenever the participant finished a block. During these longer breaks, the electrode impedances were controlled to ensure they remained below 10 kΩ.

Data Analysis

EEG processing pipeline and analysis

The electrophysiological data was preprocessed and analysed with BrainVision Analyzer (version 2.2.0). The processing pipeline was divided into two stages. The first stage focused on identifying signals that were not due to brain activity, while the second one removed these problematic components from the raw data before any further operations took place.

In the first stage, the raw data was initially filtered with a high-pass filter, employing a low cut-off of 1 Hz. A semiautomatic Independent Component Analysis (ICA) was performed, specifically to identify signals that did not originate due to cortical activity. On average, 2.6 (*SD* = 0.8) of 63 components were identified as having a non-cortical origin. These components were marked for removal in the second stage.

For the second stage, a band-pass filter, with a low cut-off of 0.05 Hz, a high cut-off of 30 Hz and a notch filter of 50 Hz, was applied to the raw EEG data. This was followed by removing the components previously identified by the ICA procedure as being unrelated to brain activity. The resulting cleaner data set was first segmented into 4000 ms time windows, specifically from -1000 ms before a conclusion was presented to a participant, to 3000 ms after, followed by a baseline correction, using the interval of -100 ms to 0 ms before a conclusion was shown. A level trigger was used to place markers for when the EOG detected vertical eye activity exceeding 100 Hz or activity exceeding 3° of horizontal eye movement. This horizontal estimate was calculated from participant’s distance from the screen, the length of the screen itself, and the amplitude of the activity recorded by the hEOG, when participants were asked to look from the middle of the screen to its horizontal borders. Trials which contained markers set by the level trigger within the first 250 ms after a conclusion was presented were removed via segmentation. An artifact rejection was performed, with a maximum allowed gradient of 50 µV/ms and an allowed maximum-minimum difference of 200 µV, both at an interval length of 200 ms, as well as a low activity criterion of 0.1

μV for an interval of 100 ms, to remove any artifacts that may have remained after prior operations. Next, an average reference was calculated, using all EEG channels, and including the implicit reference TP8. For each difficulty, wavelet analyses were performed, which used complex Morlet wavelets (c=5) with a Gabor normalization. These analyses determined the percentage increase, event-related synchronisation (ERS), and decrease, event-related desynchronisation (ERD), in power compared to the chosen reference interval, -500 ms to -100 ms before a conclusion was presented, for the frequency range of 4 Hz to 20 Hz. Per participant, the results of the time-frequency analyses were averaged. Lastly, grand averages were calculated for each difficulty, using the averaged wavelet analyses per participants.

Behavioural analysis

Raw files containing markers denoting conclusions and participant responses, as well as their timings, were extracted for all 22 participants. These files were used to determine proportions of hits and false alarms and consequently used to calculate a measure of sensitivity (d'), for each difficulty in each half of the experiment. Furthermore, the participants' mean reaction times of correctly answered conclusions were calculated, again for all three difficulties.

Firstly, the distribution of participants' mean d' and their RAPM scores was tested for normality, using the Shapiro-Wilk test, followed by calculating the correlation between participant's RAPM scores and their respective mean d' with both the Pearson correlation coefficient and Spearman's ρ. Secondly, the data was used to generate descriptive statistics and analysed via repeated measures analysis of variance (ANOVA) using linear mixed-effects models. These models were constructed with d' or reaction time as the dependent variable, the difficulty of the nonverbal syllogisms and the half of the experiment as the fixed effects, and a random effect for participants. Lastly, effect sizes (η_p^2) were calculated, and Tukey corrected post hoc comparisons were performed to investigate pairwise differences, if a significant main or interaction effect was found.

ERS/ERD

ERS and ERDs (in %μV^2) were extracted for 10 200 ms time windows starting at 900 ms and ending at 2900 ms after a conclusion was presented for the lower (θ_1: 3.2–4.8 Hz), middle (θ_2: 4.2–

6.3 Hz) and upper (θ_3: 5.5–8.2 Hz) theta bands for each difficulty per participant. The electrodes Fz, F1, and F2 were chosen for analysis. First, the data was analysed with repeated measures ANOVAs using linear mixed-effects models. These models used either the lower, middle, or upper theta power as dependent variable, the Difficulty, Window, and Electrode as fixed effects, and a random effect for participants. Secondly, the distribution of mean synchronisation for each theta band was tested for normality, using the Shapiro-Wilk test, followed by calculating correlations between participants' mean d' and their mean de/synchronisation for each theta band with the Pearson correlation coefficient and Spearman's ρ.

In line with other mass univariate studies, the criterion of significance for the repeated measures ANOVAS was adjusted based on an estimation of two successive time windows, to avoid Type 1 errors (Van der Lubbe et al., 2021). This new criterion took into account the 3 electrodes, 3 frequency bands, and 7 tests per time window that were involved in the statistical analysis. Said tests were to determine if there were main effects of Difficulty (Easy/Medium/Hard), Window (10 200 ms time windows starting at 900 ms and ending at 2,900 ms), or Electrode (Fz/F1/F2), or interaction effects for Difficulty and Window, Difficulty and Electrode, Window and Electrode, or Difficulty, Window and Electrode. This critical p-value was estimated at 0.009 ($p < \sqrt{}(0.05$ / ([nr. of time windows-1] ∗ [nr. of electrodes] ∗ [nr. of bands] ∗ [nr. of tests])) $< \sqrt{}(0.05 / (9 * 3 * 3 * 7)) < 0.00939$). Additionally, effect sizes (η_p^2) for any significant effects were calculated, and if a significant main effect for Difficulty or Electrode was found, Tukey corrected post hoc comparisons were performed to investigate pairwise differences. These employed a similar adjustment to the significance criterion, with a critical p-value estimated at 0.016 ($p < (0.05/3) < 0.01667$), as only three tests were performed per post hoc analysis. Significant interaction effects of Difficulty x Electrode similarly employed post hox analyses with a criterion for significance of 0.005 ($p < (0.05/9) < 0.00556$). As specific differences between the chosen time windows were of less interest in this research, aside from knowing if there indeed were some, significant main and interaction effects involving Window were not analysed with post hoc analyses. However, the mean changes in power per difficulty and electrode for each time window were depicted via line graphs.

Results

Behavioural data

Raven advanced progressive matrices

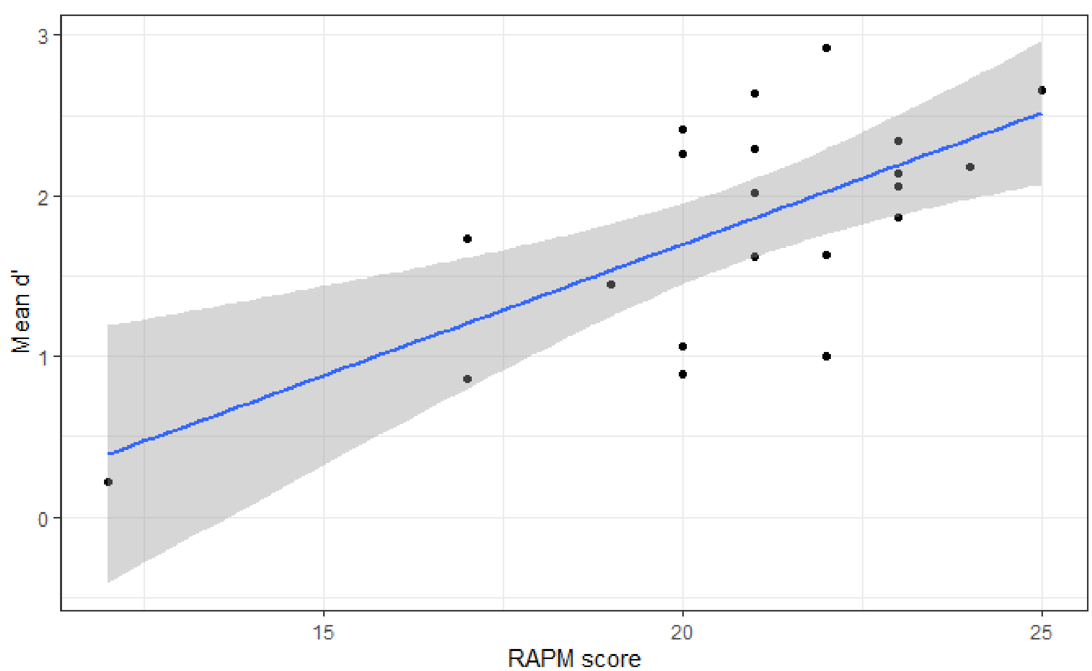
Participants' scores in the RAPM ranged from 12 correctly answered question at minimum to 25 at maximum, with a mean score of 20.8 (*SD* = 2.86). Shapiro-Wilk testing of the distribution of participants' RAPM scores determined that it did not exhibit normality ($W = .88$, $p = .018$). However, participants' mean d' appeared to be normally distributed ($W = .95$, $p = .336$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' RAPM score and their mean d'. A moderate positive correlation was found, $r(19) = .67$, $p < .001$. Consequently, according to the Pearson correlation coefficient, participants that scored high in the RAPM had some tendency to also have a higher d'.

Spearman's rank correlation was computed to assess the relationship between participants' RAPM score and their mean d'. A moderate positive correlation was found, $r(19) = .53$, $p = .013$. Consequently, according to Spearman's ρ, participants that scored high in the RAPM had some tendency to also have a higher d'.

Figure 3

Scatterplot depicting the correlation between RAPM score and mean d' for the first experiment



Nonverbal syllogisms

Analysis revealed significant main effects of Difficulty ($F(2,105) = 46.62$, $p < 0.001$, $\eta_p^2 = 0.47$) and Half ($F(1,105) = 5.49$, $p = 0.021$, $\eta_p^2 = 0.05$) on participants' d'. Furthermore, an interaction effect of Difficulty x Half on mean d' was found ($F(2,105) = 3.56$, $p = .032$, $\eta_p^2 = .06$).

Table 1

Descriptive statistics for d' and reaction time for each half of the two experiments

Experiment	Variable	Difficulty	Experiment Half			
			First		Second	
			Mean (M)	Std. Dev. (SD)	Mean (M)	Std. Dev. (SD)
First	d'	Easy	2.31	1.15	2.72	0.95
		Medium	1.48	0.91	1.97	0.75
		Hard	1.34	0.78	1.19	0.69
	Reaction time (ms)	Easy	3754.52	493.66	3335.44	347.99
		Medium	4196.28	737.28	3952.03	681.00
		Hard	4369.13	1185.37	4055.29	948.62
Second	d'	Easy	2.90	1.32	3.18	1.11
		Medium	2.32	1.08	2.47	1.16
		Hard	1.78	1.21	1.79	1.14
	Reaction time (ms)	Easy	3566.92	1404.57	2772.42	948.50
		Medium	5186.27	1425.03	4229.55	1093.89
		Hard	5976.87	2285.03	5063.26	1361.87

Tukey corrected post hoc comparisons for Difficulty determined that d' was higher in the easy difficulty compared to the medium ($p < .001$) and hard difficulty ($p < .001$). Additionally, d' was higher for the medium difficulty as compared to the hard difficulty ($p < .002$). Tukey corrected post hoc comparisons for Half determined that d' was lower in the first half of the experiment compared to the second ($p = .021$). Tukey corrected post hoc comparisons for Half x Difficulty determined that the interaction was caused by significantly lower d' in the first half of the experiment compared the second for the easy (p = .030) and medium (p = .009) difficulty. There was no difference in d' for the first and second half of the experiment for the hard difficulty (p = .420).

Reaction time

There was a significant effect of Difficulty ($F(2,105) = 16.88$, $p < .001$, $\eta_p^2 = .24$) and Half ($F(1,105) = 10.83$, $p = .001$, $\eta_p^2 = .09$) on participants' reaction times. No interaction effect was found.

Tukey corrected post hoc comparisons for Difficulty determined that reaction times were higher in the easy difficulty, compared to the medium ($p < .001$) and hard ($p < .001$) difficulty. There were no differences in reaction time between the medium and hard difficulty ($p = .493$). Tukey corrected post hoc comparisons for Half determined that reaction times were higher in the first half of the experiment compared to the second ($p = .001$)

ERS/ERD

Statistical analysis of ERS/ERD

Lower theta. Analysis revealed a main effect of Window ($F(9,1869) = 14.41$, $p < 0.001$, $\eta_p^2 = .06$) on participants' ERS/D. No significant main effects were found for Difficulty or Electrode. Neither were any interaction effects determined.

Table 2

Descriptive statistics for mean ERS/ERD for lower, middle, and upper theta for both experiments

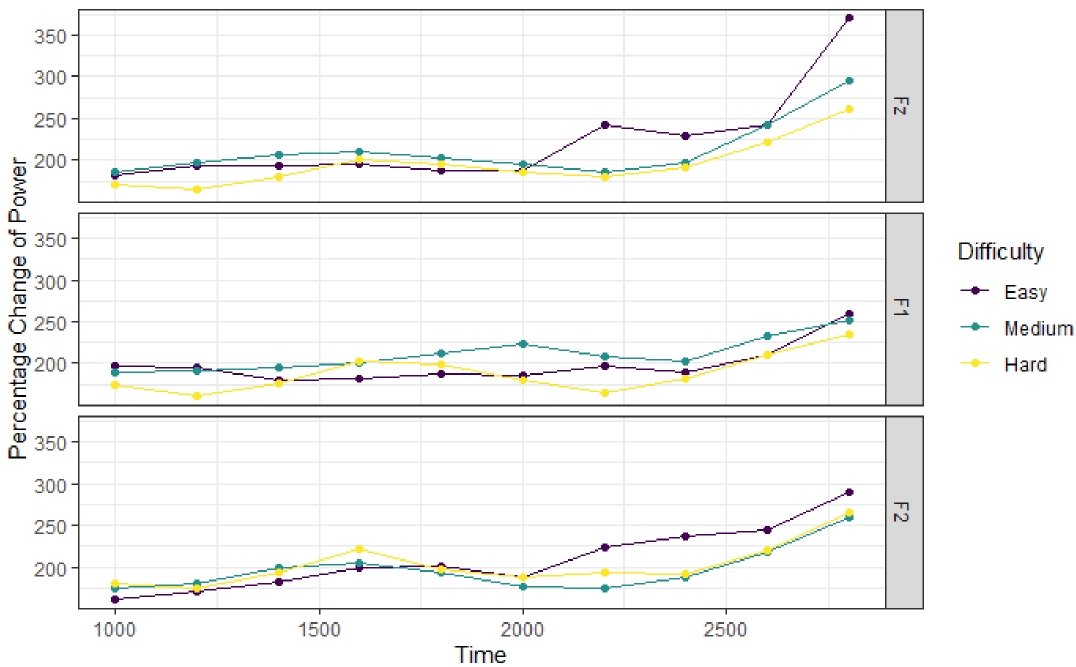
Experiment	Difficulty	Frequency band					
		Lower theta		Middle theta		Upper theta	
		Mean (M)	Std. Dev. (SD)	Mean (M)	Std. Dev. (SD)	Mean (M)	Std. Dev. (SD)
First	Easy	210.03	164.61	206.59	110.81	161.32	107.83
	Medium	206.38	84.05	234.55	141.35	181.47	136.22
	Hard	195.31	93.09	232.81	174.35	199.90	184.83

Second	Easy	193.13	92.85	177.13	90.70	159.07	114.65
	Medium	195.56	99.60	210.27	171.13	181.20	174.52
	Hard	205.38	92.39	200.72	124.67	172.29	120.41

Refer to Figure 4 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the lower theta band.

Figure 4

Line graph for the mean percentage change in theta power for the time windows in the lower theta band for Fz, F1, and F2 in the first experiment

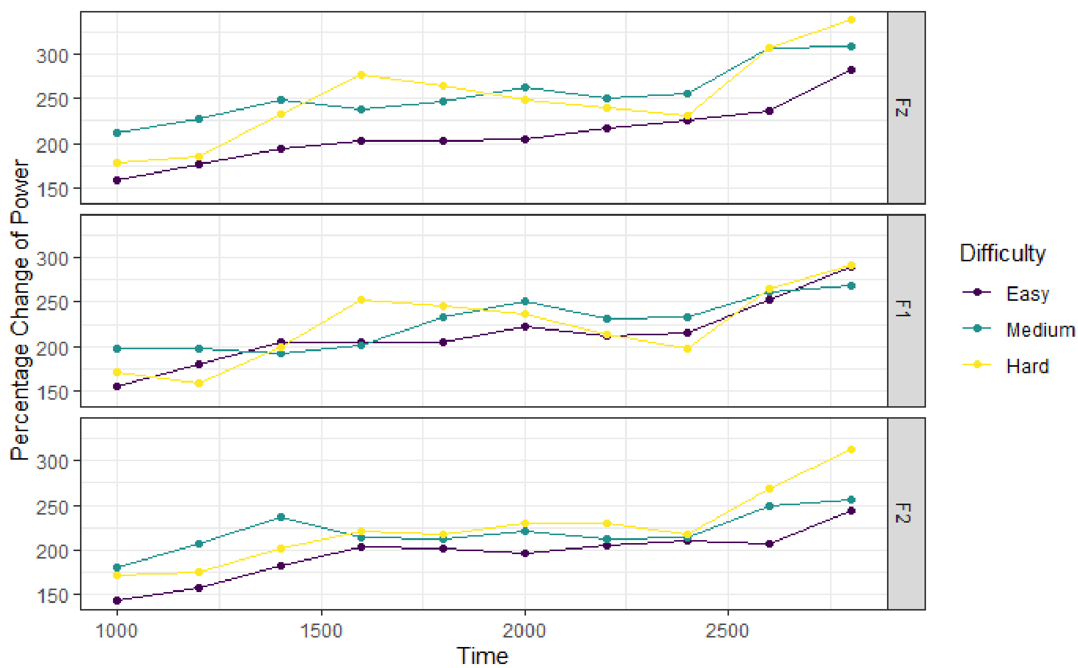


Middle theta. Analysis revealed significant main effects of Difficulty ($F(2,1869) = 18.36$, $p < .001$, $\eta_p^2 = .02$), Window ($F(9,1869) = 23.98$, $p < .001$, $\eta_p^2 = .10$) , and Electrode ($F(2,1869) = 12.58$, $p < .001$, $\eta_p^2 = .01$) on participants' ERS/D. No interaction effects were found.

Refer to Figure 5 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the middle theta band. Tukey corrected post hoc comparisons for Difficulty determined that percentage change of power was lower in the easy difficulty, compared to the medium ($p < .001$) and hard ($p < .001$) difficulty. There was no difference in ERD/S between the medium and hard difficulty (p = .940). Tukey corrected post hoc comparisons for Electrode determined that percentage change of power was higher at Fz compared to F1 (p = .002) and F2 (p < .001). No differences were found between F1 and F2 (p = .273).

Figure 5

Line graph for the mean percentage change in theta power for the time windows in the middle theta band for Fz, F1, and F2 in the first experiment

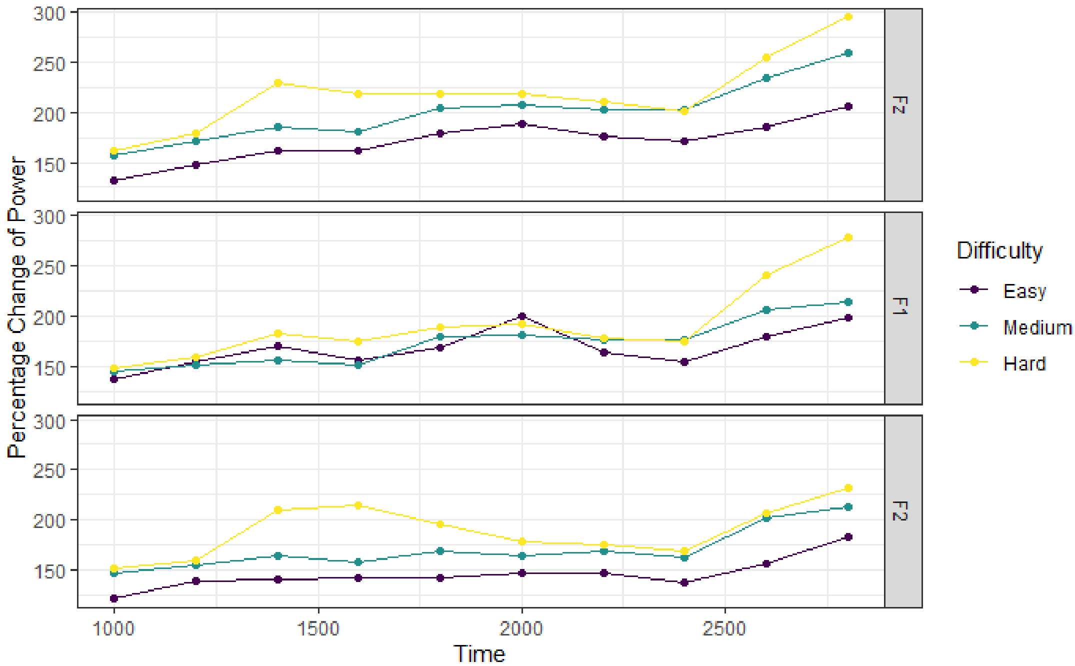


Upper theta. Analysis revealed significant main effects of Difficulty (F(2,1869) = 35.91, p < .001, η_p^2 = .04), Window (F(9,1869) = 17.08, p < .001, η_p^2 = .08) , and Electrode (F(2,1869) = 20.80, p < .001, η_p^2 = .02) on participants' ERS/D. No interaction effects were found.

Refer to Figure 6 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the upper theta band. Tukey corrected post hoc comparisons for Difficulty determined that percentage change of power was lower in the easy difficulty, compared to the medium (p < .001) and hard (p < .001) difficulty. Furthermore, synchronisation was lower in the medium difficulty compared to the hard difficulty (p < .001). Tukey corrected post hoc comparisons for Electrode determined that percentage change of power was higher at Fz compared to F1 (p < .001) and F2 (p < .001). No differences were found between F1 and F2 (p = .083).

Figure 6

Line graph for the mean percentage change in theta power for the time windows in the upper theta band for Fz, F1, and F2 in the first experiment



Correlation between performance and ERS/ERD

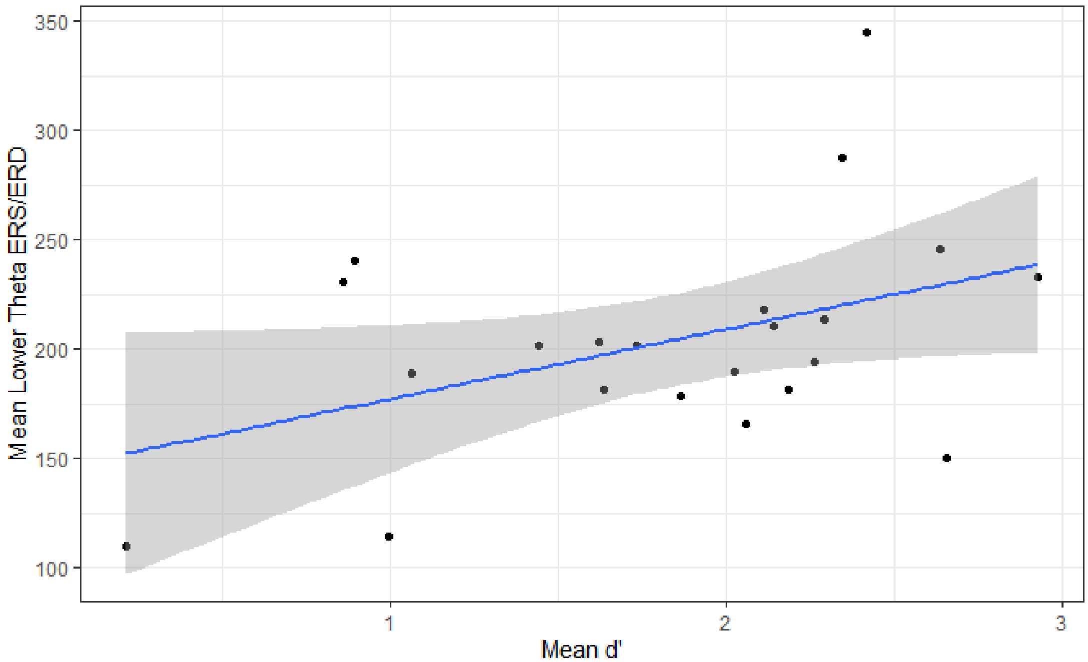
Lower theta correlation. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for lower theta determined that it did not show evidence of non-normality (W = .94, p = .205).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. A moderate positive correlation was found, r(20) = .45, p = .036. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had some tendency to also have higher mean synchronisation in the lower theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, r(20) = .39, p = . 076. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the lower theta band.

Figure 7

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the lower theta band for the first experiment



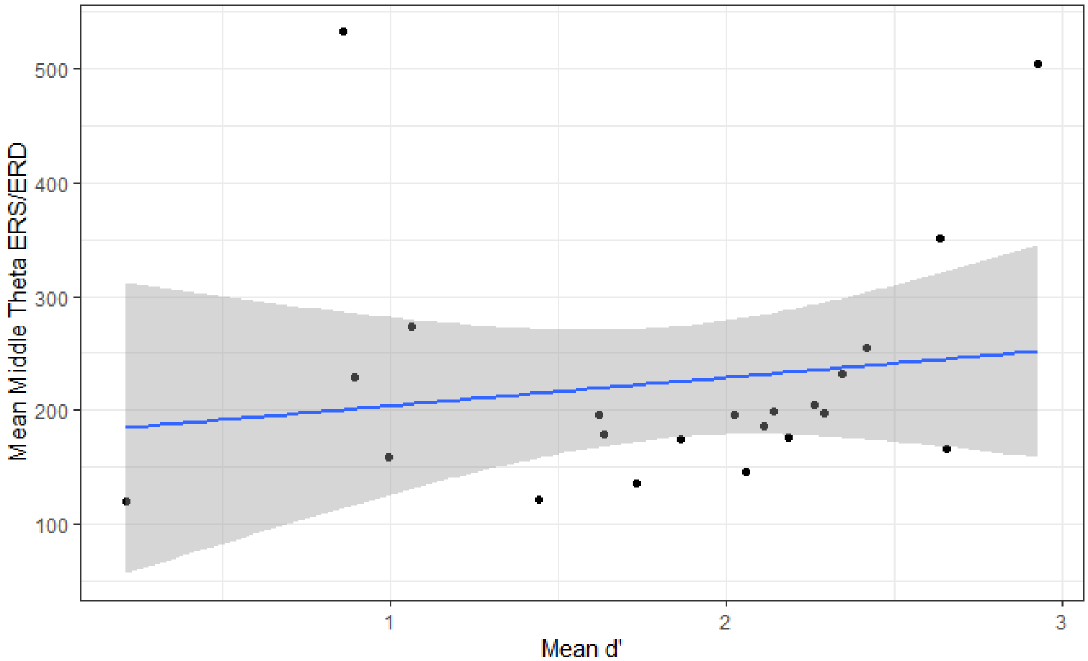
Middle theta correlation. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for middle theta determined that it did not exhibit normality ($W = .75$, $p < .001$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(20) = .19$, $p = .396$. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the middle theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(20) = .35$, $p = .\ 107$. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the middle theta band.

Figure 8

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the middle theta band for the first experiment



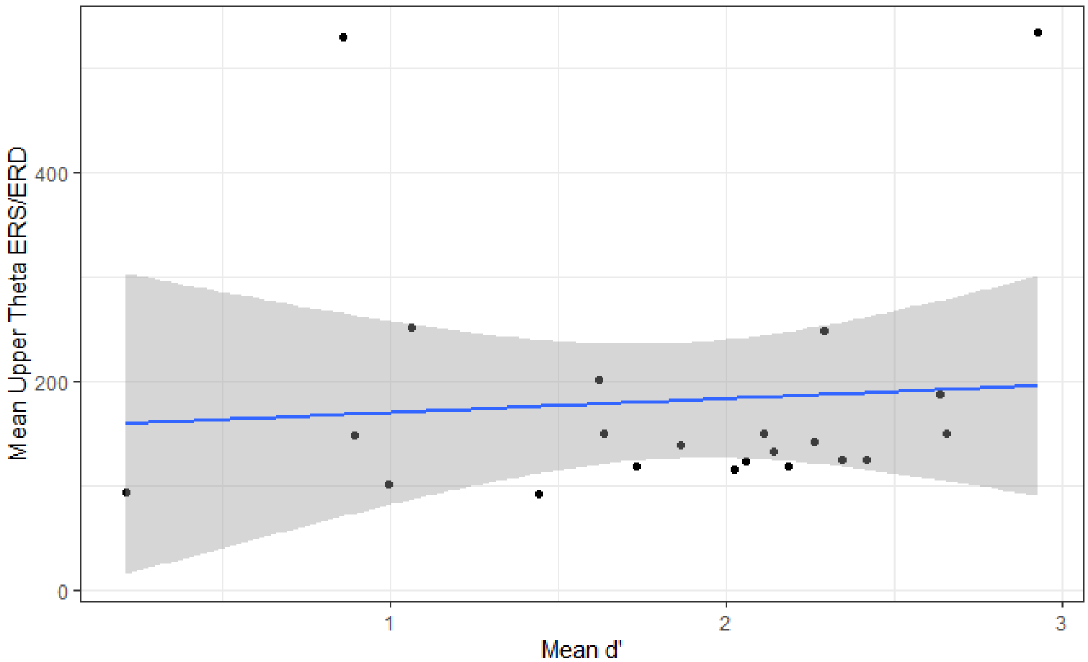
Upper theta correlation. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for upper theta determined that it did not exhibit of normality ($W = .63$, $p < .001$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(20) = .11$, $p = .627$. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the upper theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(20) = .30$, $p = .180$. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the upper theta band.

Figure 9

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the upper theta band for the first experiment

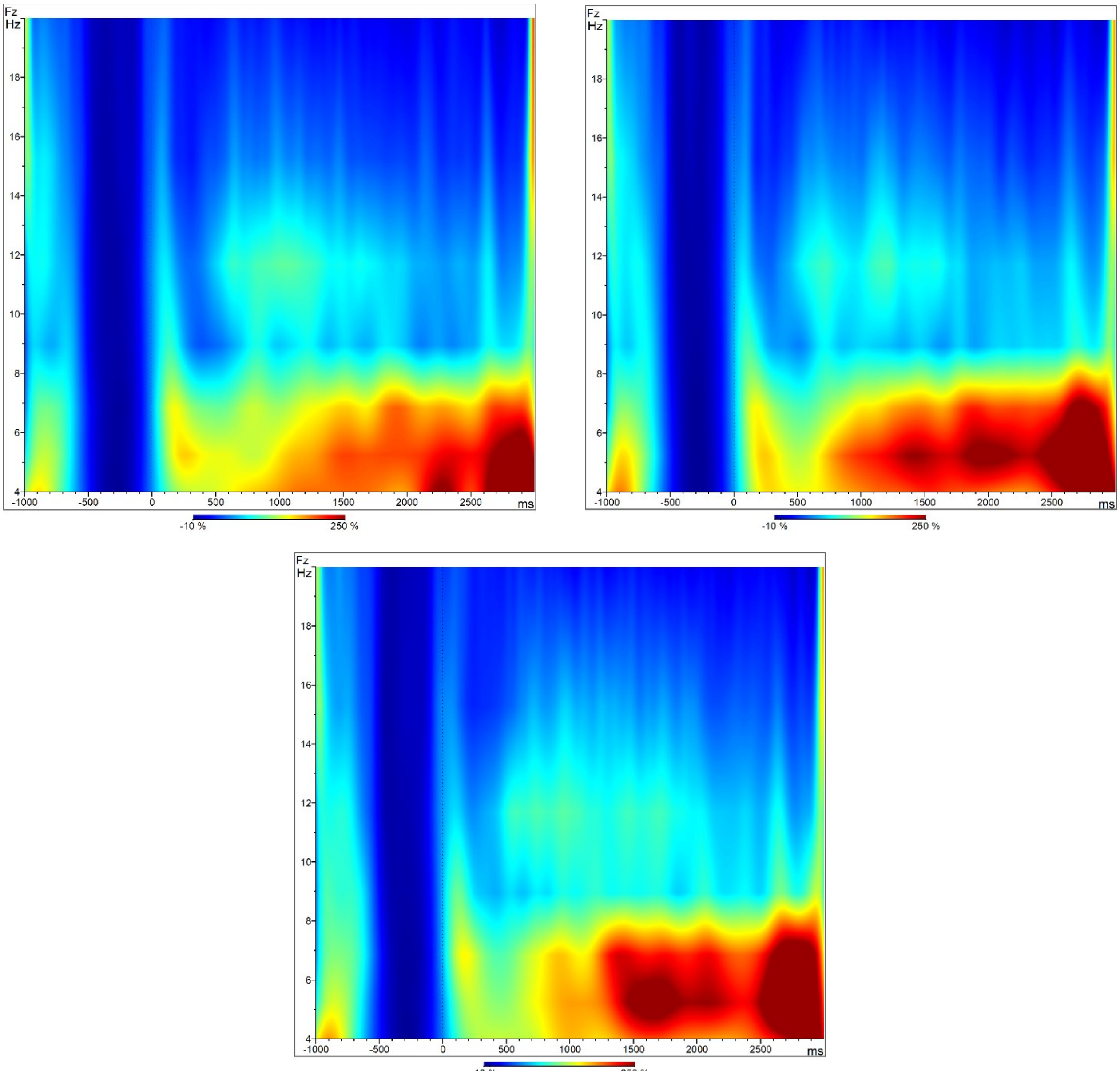


Visual inspection of time-frequency graphs

The time-frequency graphs generated by the wavelet analyses shown in Figure 10 depict notable activity across the whole theta band for all difficulties after the presentation of a conclusion for the first experiment. Universally, aside from a brief burst of theta activity when a conclusion was revealed, theta activity appeared to increase over the period from 700 ms to 1,000 ms after the presentation of a conclusion. The extent of this increase and the times at which activity subsequently peaked differed for each difficulty, however, commonly there appeared periods of high synchronisation around 1,600 ms, 2,000 ms, and 2,800 ms after a conclusion was presented.

Figure 10

Time-frequency graphs generated by the wavelet analyses for the first experiment

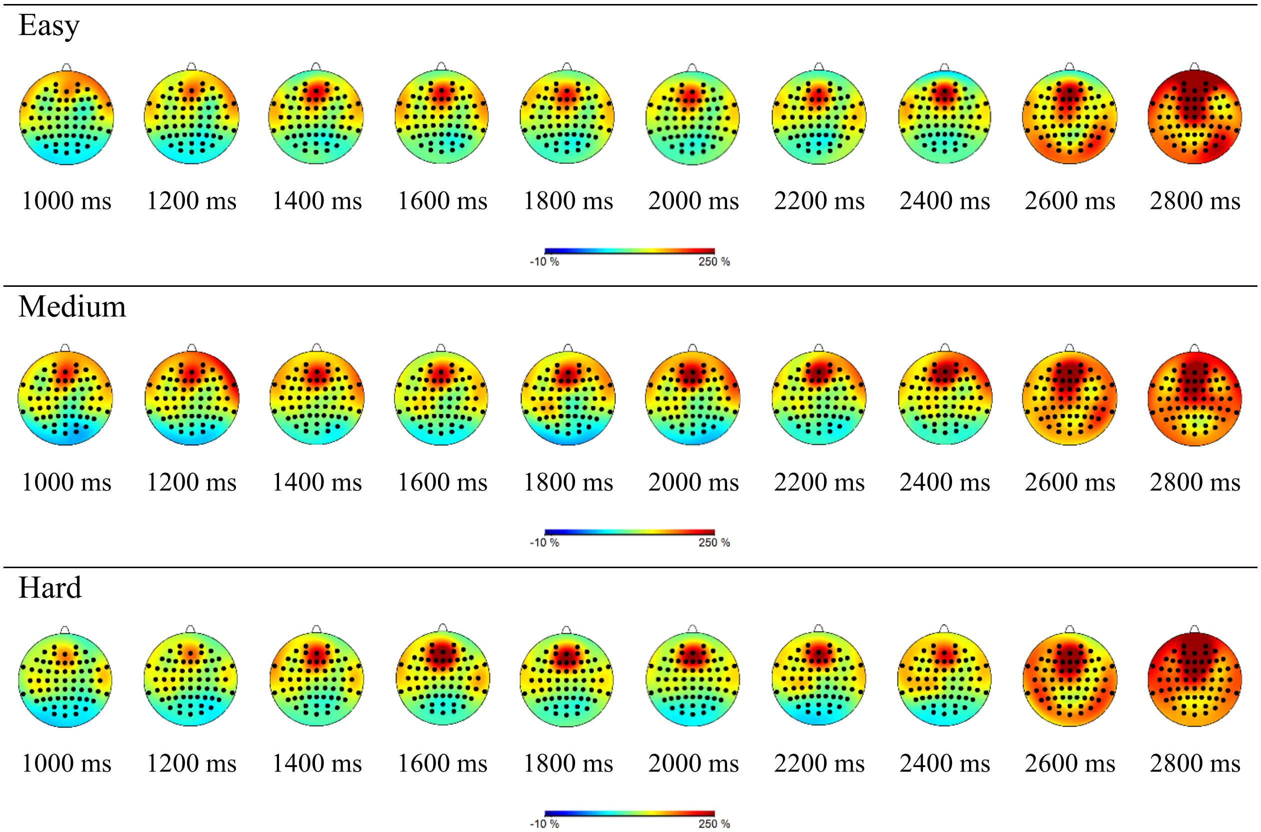


Note. The graphs depict the easy (top left), medium (top right), and hard (bottom middle) difficulty for electrode Fz, generated via BrainVision Analyzer (n.d.), in the first experiment. Activity from 4 Hz to 20 Hz is displayed. The chosen baseline period was -500 ms to -100 ms and depicted activity is scaled from -10% (blue) up to 250% (red).

The topographies generated by the wavelet analyses shown in Figure 11 depict notable theta activity for all difficulties along at the frontal midline, particularly at Fz, after the presentation of a conclusion for the second experiment. Especially in the higher difficulties, there is clear frontal midline theta rhythm, which persists for the majority of the time windows. Universally, theta activity is more widespread from the 2,600 ms time window onwards. While strong frontal midline theta activity can still be observed, there also appears activity at anterior, temporal and occipital sites.

Figure 11

Topographies generated by the wavelet analyses for the first experiment



Note. The topographies depict the easy (top), medium (middle), and hard (bottom) difficulty for electrode Fz, generated via BrainVision Analyzer (n.d.) for the midpoints of the time windows chosen for analysis for the first experiment. Activity at 5.27 Hz is displayed. Depicted activity is scaled from -10% (blue) up to 250% (red).

Discussion

The objective of this first experiment was to validate nonverbal syllogisms as measures of working memory and consequently of fluid intelligence as well. To that end, general predictions were made based upon the findings of prior literature. By and large, the findings of this first experiment fell in line with the general predictions, however they also differed in some key respects, which will be noted here. The findings will be discussed in greater detail in the general discussion.

First and foremost, a moderate correlation between participants' RAPM score and their mean sensitivity was found. Consequently, participants that scored highly on the RAPM also had a fair chance at being better able to correctly evaluate nonverbal syllogisms. This fell in line with the general prediction that as measures of fluid intelligence, RAPM scores and performance in evaluating nonverbal syllogisms would be correlated. Furthermore, participants' sensitivity and reaction time decreased as difficulty increased, much like initially predicted, albeit this difference was more pronounced when comparing the easy difficulty to the medium and hard difficulties. Differences between the behavioural data in the medium and hard difficulties were far less distinct, especially with reaction time not differing at all. Additionally, the findings clearly showed that participants improved in their performance, as they showed both higher sensitivity in correctly evaluating nonverbal syllogisms and higher reaction times in the second half of the experiment as compared to the first. It must be noted that for sensitivity this was only the case for the easy and medium difficulties, as there was no difference in performance between the first and second half of the experiment.

Similar trends as for the behavioural data were found for the ERS and ERDs, again partially falling in line with the initial predictions. Theta power notably increased as difficulty increased, however this was only the case for middle and upper theta bands. Furthermore, while for the upper theta bands all difficulties had different levels of theta power, for middle theta there were only differences when comparing the easy difficulty with either the medium or hard difficulty. Beyond that, it was predicted that activity would be highest at the frontal midline, which is quite clearly represented here. Fz, or rather the frontal midline, was clearly the centre of activity in this first experiment. F1 nor F2 did not exceeded Fz's levels of synchronization or differ in some way from one another. Lastly, the prediction was made that participants' sensitivity in correctly evaluating nonverbal syllogisms and their corresponding theta activity would be correlated. Notably, this was only the case for the lower theta band, as the middle and upper theta band showed no correlation between participants mean sensitivity and their mean synchronisation.

Experiment 2: Using nonverbal syllogisms to test spatial reasoning

In the first experiment, participants only needed to evaluate if the figures shown in the premises were directly next to one another and in the order given by the premises. As such, they faced a straightforward memory task, simply prompting them to memorise the relevant figures and their order. No further mental manipulation was required to be able to evaluate the following conclusions. This resulting in measurable theta activity, which increases with higher difficulties has been noted in numerous past studies (Ishihara & Yoshii, 1972; Jensen & Tesche, 2002; Klimesch et al., 1996; Maurer et al., 2015; Qiu et al., 2009; Roberts et al., 2013). The findings of the first experiments already suggested that nonverbal syllogisms may serve as a suitable tool to measure fluid intelligence via working memory, on account of them supporting the general predictions. However, nonverbal syllogisms hold further potential for measuring other aspects, depending upon how they are constructed. This second experiment set out to demonstrate as such.

The objective of this second experiment was to explore this potential by altering the nature of the nonverbal syllogisms to test spatial ability, or more specifically, spatial reasoning. Lohman (1996) defined spatial ability as the capacity to "generate, retain, retrieve, and transform well-structured visual images" (p. 3), and argues that it is one of the major ways to test for fluid intelligence. It is considered another aspect of fluid intelligence that is related to, but distinct from, working memory (Lohman, 1996). Spatial reasoning in this research is further defined as the ability to form a mental understanding of objects, realise their spatial relations to other objects, and successfully manipulate these objects and relations. Much like working memory and fluid intelligence in general, spatial reasoning has previously been associated with the prefrontal cortex and theta activity, albeit not specifically with the frontal midline theta rhythm (Duncan et al., 2000). Regardless of this, large similarities to the findings of the first experiment were expected when investigating spatial reasoning.

In this second experiment, nonverbal syllogisms were constructed in such a fashion that the premises implied both direct and indirect spatial relation which the participant had to realise and memorize. Based upon these spatial relations, conclusions had to be evaluated. Additionally, due to the perceived higher demands placed upon participants, and the potential of overburdening participants working memory, it was decided that conclusions should not be hidden as in the first experiment. While there was still an element of memorization, it was judged that spatial reasoning played a greater part in the correct evaluation of nonverbal syllogisms and trends related to it could be more easily identified.

Method

Participants

In total, twenty-seven individuals participated in the second experiment. Six participants had to be excluded, five due to technical complications with the equipment and one due to not fully following instructions. Participants were again recruited via the Test Subject Pool SONA from the current and past student population of the University of Twente. The twenty-one participants that qualified for analysis (M_{age} = 21.1 years, *SD* = 2.7; 9 German, 5 Dutch, 7 Other; 13 female, 8 male; 17 right-handed, 2 left-handed, 2 ambidextrous) reported normal or corrected-to-normal vision, indicated they had no histories of cognitive disorders, physical injuries or impairments, drug or alcohol addictions, and had used no medication prior to the experiment. This experiment received ethical approval (Requestnr.: 221003) from the BMS Ethics Committee of the University of Twente.

Stimuli and Task

Raven advanced progressive matrices

The same RAPM version was used in this second experiment as in the first and in the same manner.

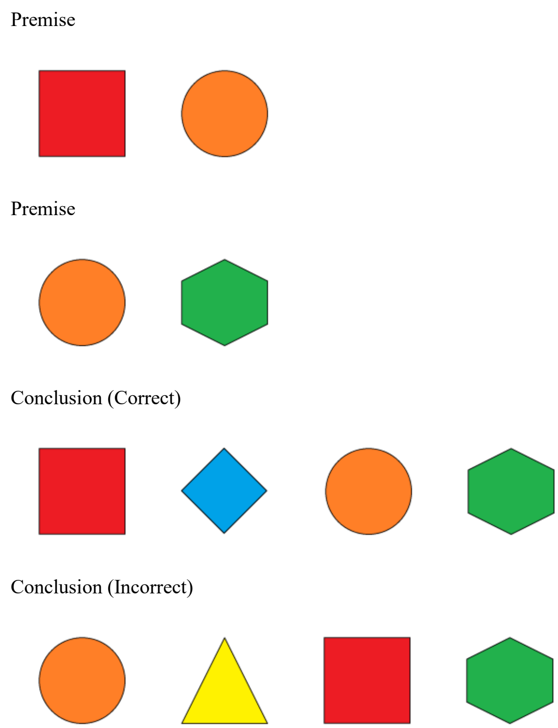
Nonverbal syllogisms

The task given to the participant in this experiment remained largely the same as in the first experiment. Participants were given premises, with the number varying depending on the difficulty of the block, before they were asked to evaluate several conclusions based upon said premises. There were again six blocks, with two for each difficulty. Each block contained five sets of premises and conclusions, and each set contained ten conclusions. The experiment was split into two halves, as in the first experiment, so that participants would only encounter each difficulty once per half.

However, nonverbal syllogisms were constructed differently. Premises still gave the order in which the figures had to appear in conclusions, but these orders now had to be maintained regardless of what appeared in between shown figures. As such, premises rather prescribed overarching spatial relations rather than exact orders to memorize. Additionally, if two premises shared a figure, they formed an indirect relationship between the figures of the premises that shared said figure. There was always at least one such indirect relationship for every set of premises, although at the higher difficulties there could be multiple such indirect relationships. Refer to Figure 12 for an example of a set of premises, as well as conclusions that feature spatial relations.

Figure 12

Example of a set of premises and conclusions as used in the second experiment

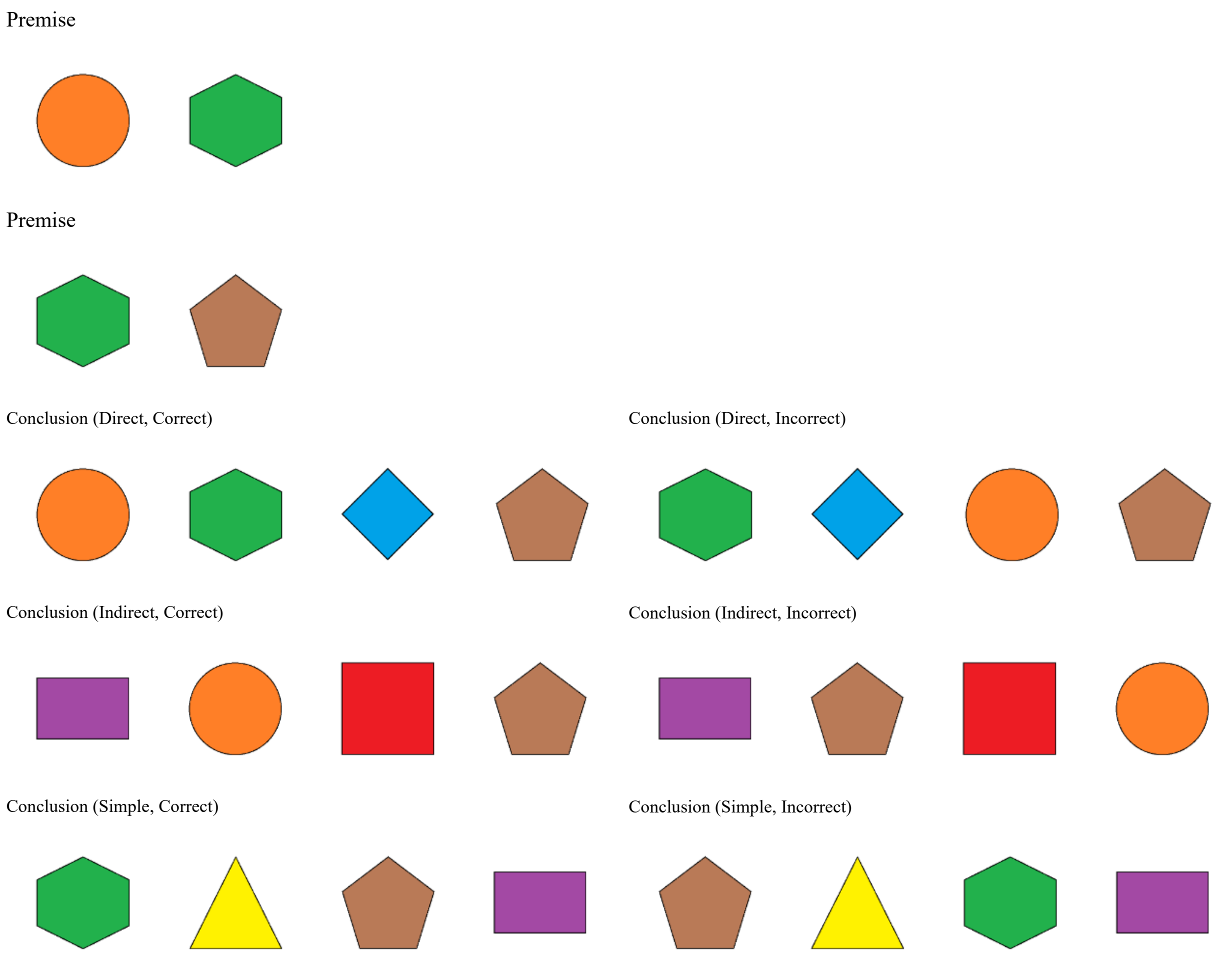


Note. Example of a nonverbal syllogism employed in the second experiment, showing two premises (above) used to evaluate two conclusions (below). The premises can be verbally described as “red square must be in front of orange circle if both appear in the conclusion” and “orange circle must be in front of green hexagon if both appear in the conclusion.” Additionally, there is an indirect relation due to both premises containing the orange circle, which can be verbally described as “red square must be in front of green hexagon if both appear in the conclusion.” In the first conclusion all figures are in the orders given by the premises, making it correct, while in the second, the orange circle appears in front of the red square, making it incorrect.

While participants again had to evaluate a total number of 300 conclusions, said conclusions were more structured in this second experiment than in the first. Namely, there were three types of conclusion types, direct conclusions that featured direct spatial relations from two premises at a minimum, indirect conclusions that featured one indirect spatial relation at a minimum, and simple conclusions which featured only one direct relation from the premises. Direct and indirect conclusions were of greater interest in this experiment, and as such there were four of each in every set of conclusions, with two being correct and two incorrect. Conversely, there were only two simple conclusions per set, with one correct and one incorrect. Per block there were 20 direct, 20 indirect and 10 simple conclusions, equally divided between each set of premises and conclusions. Refer to Figure 13 for examples of each type of conclusion as they might have appeared in the experiment. Participants gave their response to conclusions in the same fashion as in the first experiment, a left button press to indicate a conclusion was correct, and a right button press to indicate a conclusion was incorrect.

Figure 13

Examples for each type of conclusion used in the second experiment

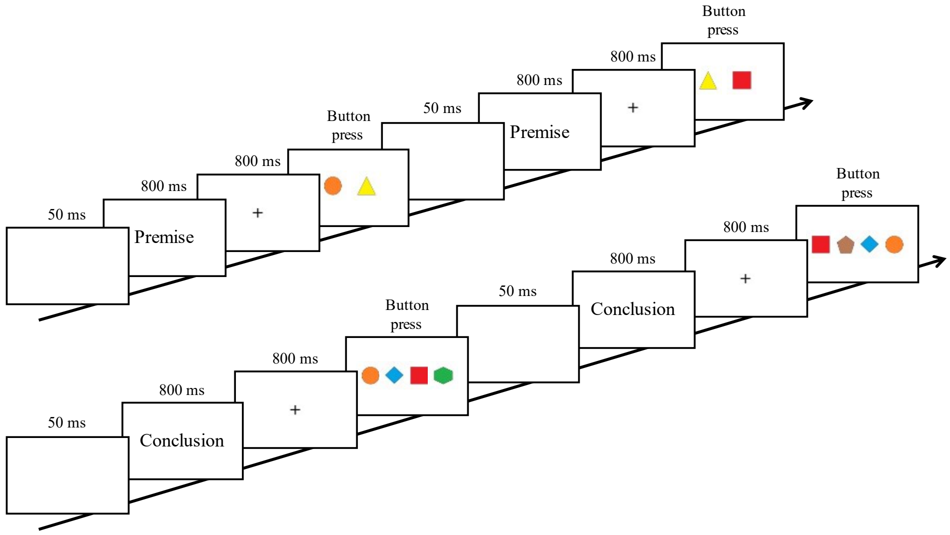


Note. Example of a nonverbal syllogism employed in the second experiment, showing two premises (above) used to evaluate three types of conclusions (below), with one correct (left) and one incorrect (right) for each type The first row of conclusions shows direct conclusions which always use at least two of the spatial relations given by the premises. The second row of conclusions uses indirect relations, which are formed due to the green hexagon being present in both premises. The last row contains simple conclusions, which only ever use one direct spatial relation given by a premise.

Two further differences to the first experiment were that conclusions were not hidden 2,500 ms after being presented and that participants were able to respond at any time after the conclusion was shown. Refer to Figure 14 for a visual representation of the stimuli timeline used in the second experiment.

Figure 14

Stimuli timeline for the second experiment



Note. Stimuli timeline for the presentation of a set of premises (above) and conclusions (below) like those used in the first experiment. Text above the images corresponds to how long a specific screen would be shown. A set of trials began by presenting participants with premises, which were viewable until the participant decided to advance the screen and repeated once. After 1,650 ms passed, participants saw their first conclusion. Conclusions were presented one at a time and participants could answer at any time after the conclusion was shown. Participants were only shown the next conclusion 1,650 ms after they gave a response.

Procedure

The same procedure was employed in this second experiment as the first experiment.

Data Analysis

EEG processing pipeline and analysis

The EEG processing pipeline was largely the same as the first experiment, with two exceptions. Firstly, on average only 2.3 (*SD* = 0.6) of 63 components were identified as being unrelated to brain activity by the ICA procedure and consequently removed. Secondly, trials in which participants responded within 1,000 ms after a conclusion was presented were removed, to ensure that the data of very early responses would not influence later statistical analysis.

Behavioural analysis

The behavioural analysis employed the same methodology as in the first experiment for checking participants' d' and mean reaction times.

ERS/ERD

The same time windows as in the first experiment were analysed, replicating the process for analysis that was employed in the first experiment, to test the general hypotheses with another independent sample.

Results

Behavioural data

Raven advanced progressive matrices

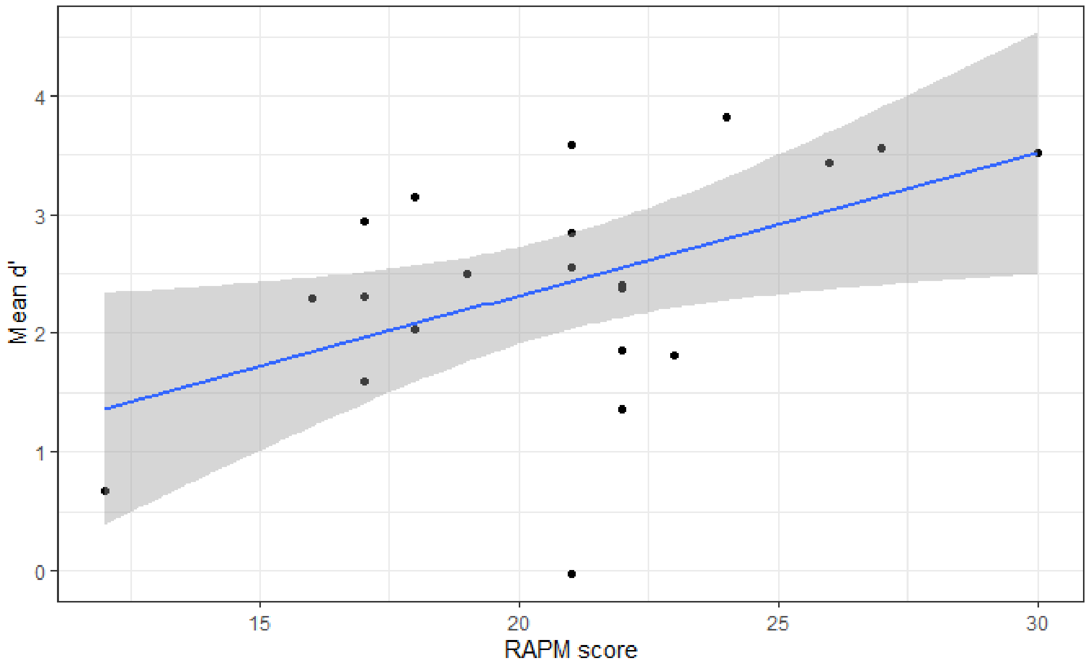
Participants' scores in the RAPM ranged from 12 correctly answered question at minimum to 30 at maximum, with a mean score of 20.8 (SD = 4.09). Shapiro-Wilk testing of the distribution of participants' RAPM scores showed evidence of it being normally distributed (W = .97, p = .752). The same was the case for participants' mean d' (W = .95, p = .324).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' RAPM score and their mean d'. A moderate positive correlation was found, $r(19)$ = .49, p = .023. Consequently, according to the Pearson correlation coefficient, participants that scored high in the RAPM had some tendency to also have a higher d'.

Spearman's rank correlation was computed to assess the relationship between participants' RAPM score and their mean d'. No correlation was found, $r(20)$ = .42, p = .061. Consequently, according to the Spearman's ρ, participants that scored high in the RAPM had no tendency to also have a higher d'.

Figure 15

Scatterplot depicting the correlation between RAPM score and mean d' for the second experiment



Nonverbal syllogisms

Analysis revealed a significant main effect of Difficulty ($F(2,100) = 34.78$, $p < 0.001$, $\eta_p^2 = 0.41$) on participants' d'. No main effect of Half or interaction was found.

Tukey corrected post hoc comparisons for Difficulty determined that d' was higher in the easy difficulty, compared to the medium ($p < .001$) and hard ($p < .001$) difficulty. Additionally, d' was higher in the medium difficulty as compared to the hard difficulty ($p < .001$).

Reaction time

There was a significant effect of Difficulty ($F(2,100) = 52.60$, $p < .001$, $\eta_p^2 = .51$) and Half ($F(1,100) = 21.84$, $p < .001$, $\eta_p^2 = .18$) on participants' reaction times. No interaction effect of Difficulty x Half on reaction time was found.

Tukey corrected post hoc comparisons for Difficulty determined that reaction times were higher in the easy difficulty, compared to the medium ($p < .001$) and hard ($p < .001$) difficulty. Additionally, reaction times were higher for the medium difficulty as compared to the hard difficulty ($p = 0.002$). Tukey corrected post hoc comparisons for Half determined that reaction times were higher in the first half of the experiment compared to the second ($p < .001$)

ERS/ERD

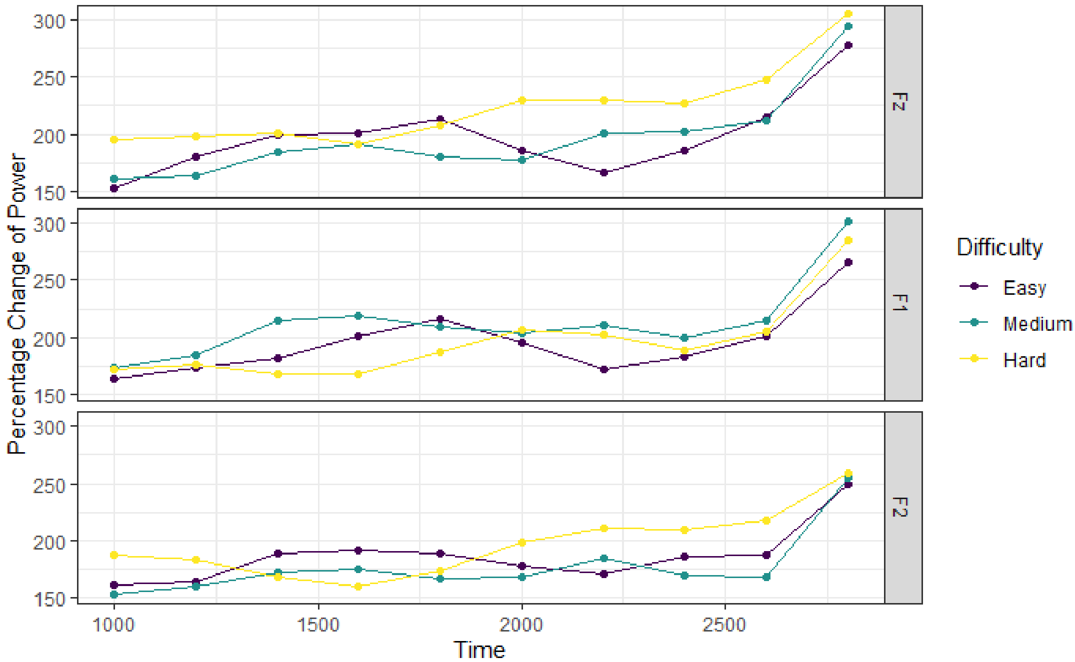
Statistical analysis of ERS/ERD

Lower theta. Analysis revealed significant main effects of Window ($F(9,1780) = 24.77$, $p < .001$, $\eta_p^2 = .11$) and Electrode ($F(2,1780) = 9.33$, $p < .001$, $\eta_p^2 = .01$) on participants' ERS/D. Furthermore, an interaction effect of Difficulty x Electrode on participants' ERS/D was found ($F(4,1780) = 4.75$, $p = .001$, $\eta_p^2 = .01$). No significant main effects were found for Difficulty or Electrode. Neither were any further interaction effects determined.

Refer to Figure 16 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the lower theta band. Tukey corrected post hoc comparisons for Electrode determined that synchronisation was higher at Fz compared to F2 ($p = .001$). Furthermore, there was higher synchronisation at F1 compared to F2 ($p = .004$). There was no difference in ERD/S between Fz and F1 ($p = .608$). Tukey corrected post hoc comparisons for Difficulty x Electrode determined that the interaction was caused by significantly higher synchronisation at Fz in the hard difficulty compared to the easy ($p = .004$) and medium ($p = .002$) difficulty. No further difference between the easy and medium difficulty was found at Fz ($p = .992$), nor were any significant differences in synchronisation between difficulties determined for F1 and F2.

Figure 16

Line graph for the mean percentage change in power for the time windows in the lower theta band for Fz, F1, and F2 in the second experiment

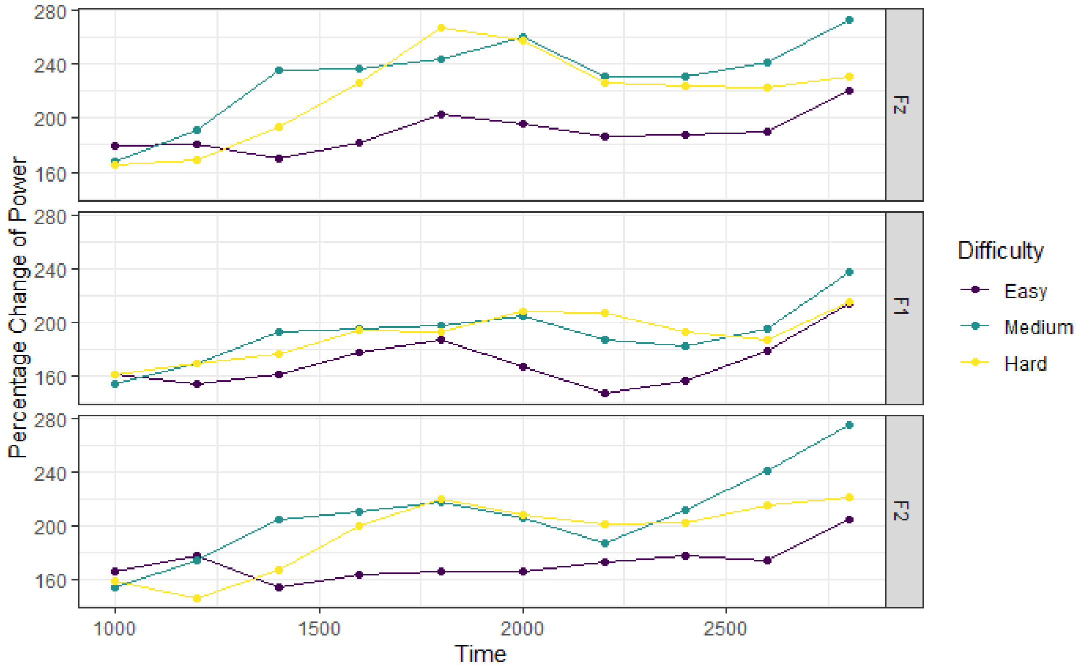


Middle theta. Analysis revealed significant main effects of Difficulty ($F(2,1780) = 21.49$, $p < 0.001$, $\eta_p^2 = .02$), Window ($F(9,1780) = 9.13$, $p < 0.001$, $\eta_p^2 = .04$) , and Electrode ($F(2,1780) = 17.08$, $p < 0.001$, $\eta_p^2 = .02$) on participants' ERS/D. No interaction effects were found.

Refer to Figure 17 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the middle theta band. Tukey corrected post hoc comparisons for Difficulty determined that percentage increase of power was lower in the easy difficulty, compared to the medium ($p < .001$) and hard ($p < .001$) difficulty. There was no difference in ERS between the medium and hard difficulty ($p = .158$). Tukey corrected post hoc comparisons for Electrode determined that percentage increase of power was higher at Fz compared to F1 ($p < .001$) and F2 ($p = .001$). No differences were found between F1 and F2 ($p = .324$).

Figure 17

Line graph for the mean percentage change in power for the time windows in the middle theta band for Fz, F1, and F2 in the second experiment

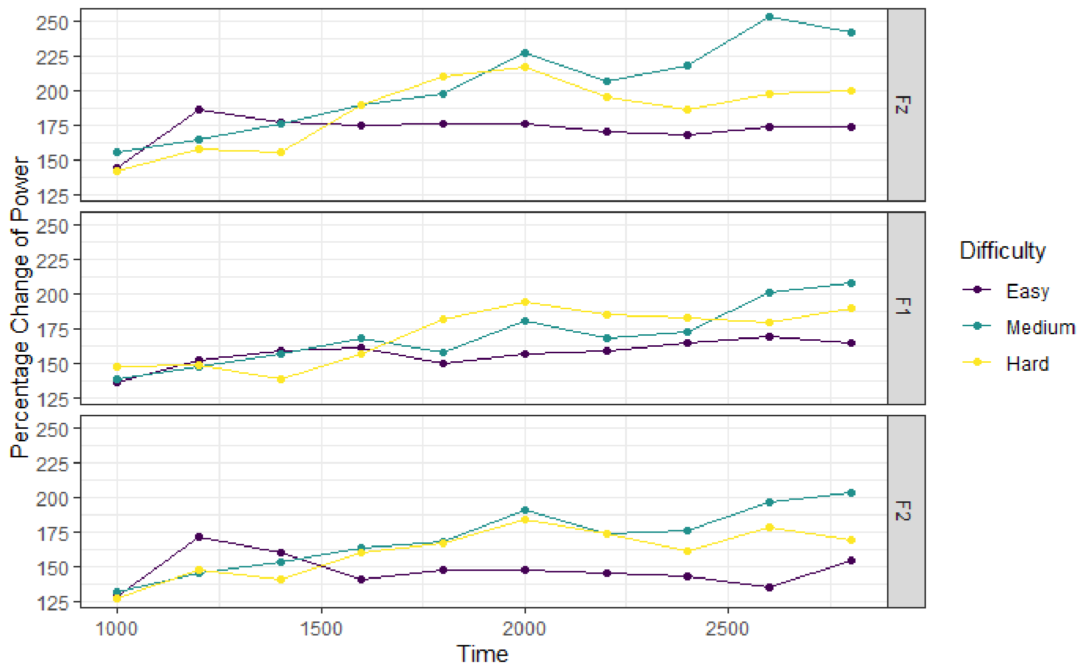


Upper theta. Analysis revealed significant main effects of Difficulty ($F(2,1780) = 11.16$, $p < 0.001$, $\eta_p^2 = .01$), Window ($F(9,1780) = 6.71$, $p < 0.001$, $\eta_p^2 = .03$) , and Electrode ($F(2,1780) = 17.70$, $p < 0.001$, $\eta_p^2 = .02$) on participants' ERS/D. No interaction effects were found.

Refer to Figure 18 for a visual depiction of mean theta power percentage change per time window, for each difficulty in the upper theta band. Tukey corrected post hoc comparisons for Difficulty determined that percentage increase of power was lower in the easy difficulty, compared to the medium ($p < .001$) and hard ($p = .014$) difficulty. There was no difference in ERS between the medium and hard difficulty ($p = .142$). Tukey corrected post hoc comparisons for Electrode determined that percentage change of power was higher at Fz compared to F1 ($p < .001$) and F2 ($p < .001$). No differences were found between F1 and F2 ($p = .390$).

Figure 18

Line graph for the mean percentage change in power for the time windows in the upper theta band for Fz, F1, and F2 in the second experiment



Correlation between performance and ERS/ERD

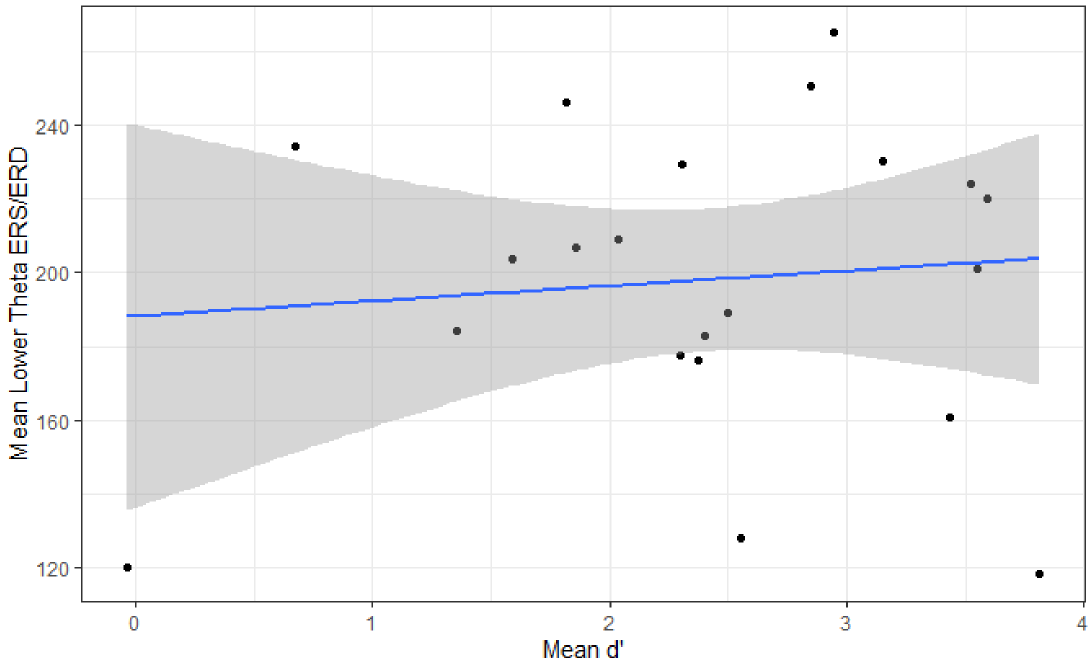
Lower theta. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for lower theta determined that it showed evidence of being normally distributed ($W = .95$, $p = .346$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = .10$, $p = .674$. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the lower theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = -.02$, $p = .935$. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the lower theta band.

Figure 19

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the lower theta band for the second experiment



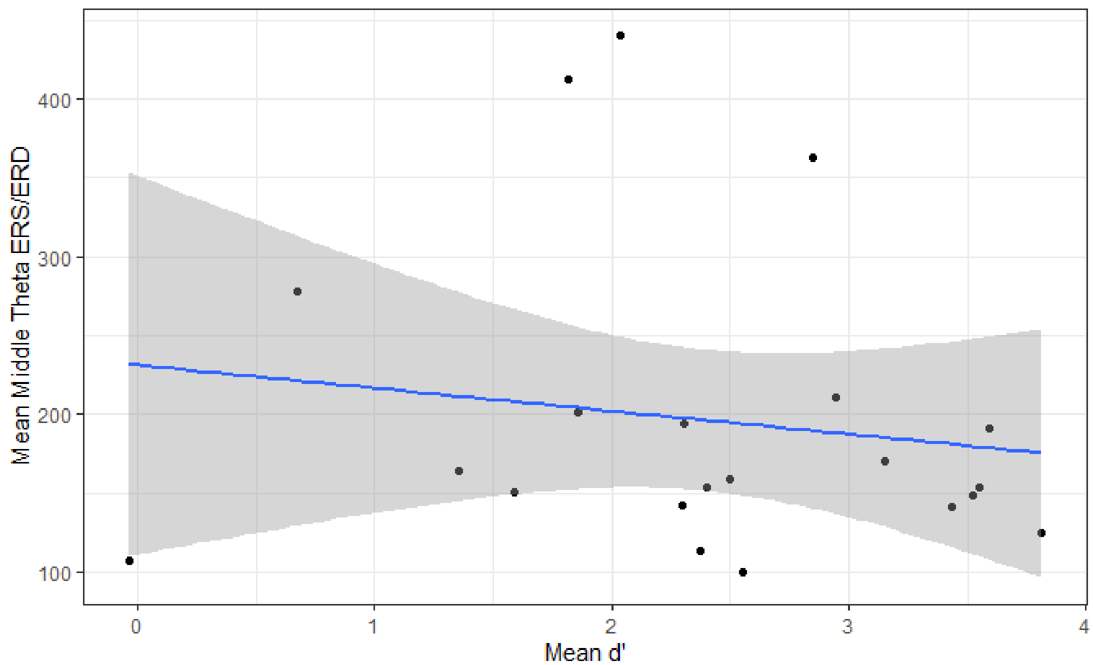
Middle theta. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for lower theta determined that it did not exhibit normality ($W = .78$, $p < .001$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = -.15$, $p = .518$. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the lower theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = -.19$, $p = .399$. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the lower theta band.

Figure 20

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the middle theta band for the second experiment



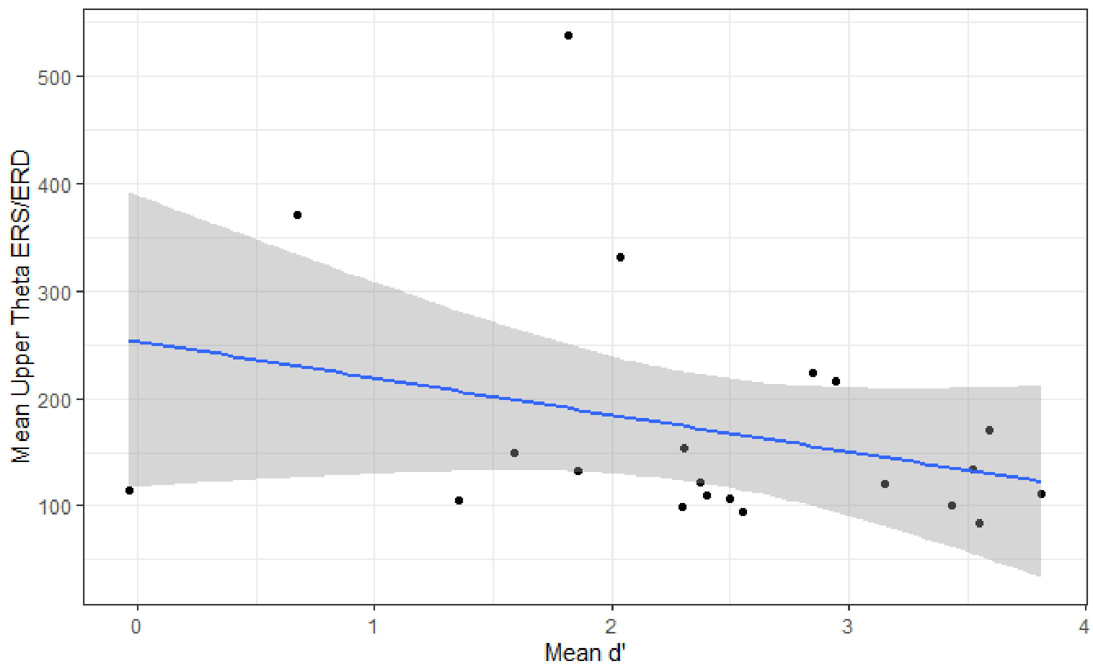
Upper theta. Shapiro-Wilk testing of the distribution of participants' mean ERS/ERD for lower theta determined that it did not exhibit normality ($W = .70$, $p < .001$).

A Pearson correlation coefficient was computed to assess the linear relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = -.30$, $p = .186$. Consequently, according to the Pearson correlation coefficient, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the upper theta band.

Spearman's rank correlation was computed to assess the relationship between participants' mean d' and their mean ERS/ERD. No correlation was found, $r(19) = -.25$, $p = .277$. Consequently, according to Spearman's ρ, participants that had a high mean d' had no discernible tendency to also have a higher mean synchronisation in the upper theta band.

Figure 21

Scatterplot depicting the correlation between mean d' and mean ERS/ERD in the upper theta band for the second experiment

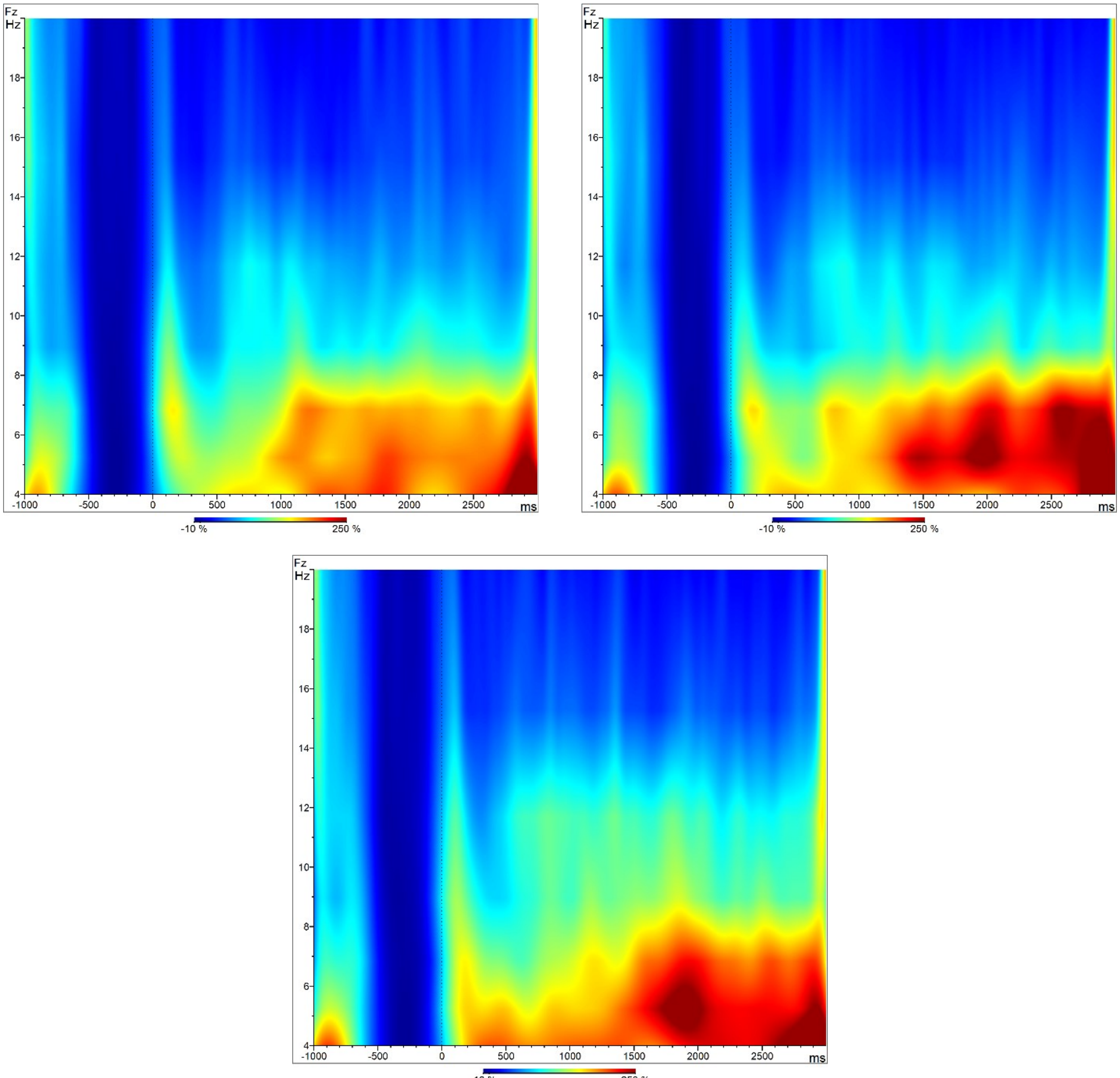


Visual inspection of time-frequency graphs

The time-frequency graphs generated by the wavelet analyses shown in Figure 22 depict notable activity across the whole theta band for all difficulties after the presentation of a conclusion for the second experiment. In all difficulties there appeared a brief burst in activity along the whole theta band. For the higher ranges of the frequency band, this burst only had a short duration, however, continuous activity was recorded along the lower theta range for the entire 3,000 ms depicted, especially in the medium and higher difficulties. Furthermore, theta activity increased for the higher theta ranges from 700 ms onwards as well. The extent of this increase, the times at which activity subsequently peaked, and the number of times it did so differed for each difficulty, however, commonly there appeared to be periods of high synchronisation around 1,500 ms, 1,900 ms, and 2,900 ms after a conclusion was presented.

Figure 22

Time-frequency graphs generated by the wavelet analyses in the second experiment

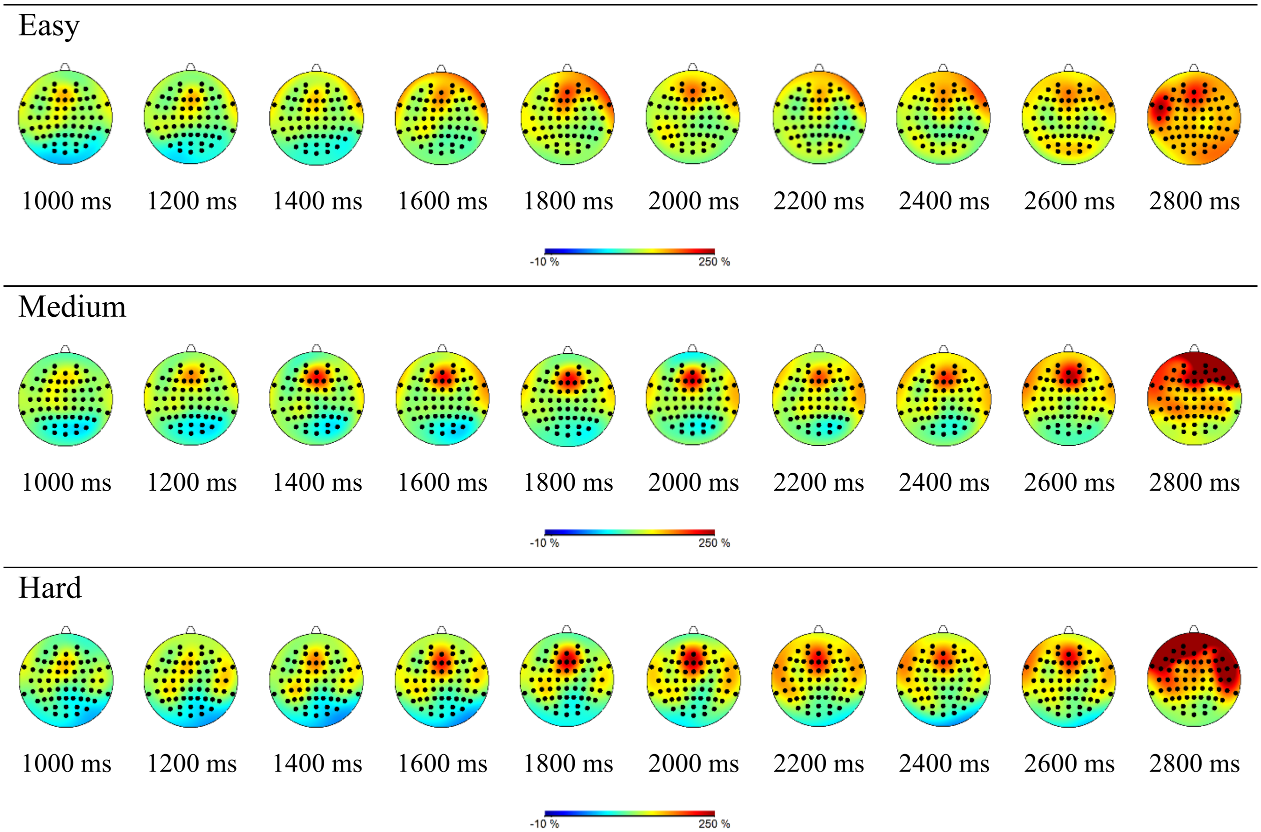


Note. The graphs depict the easy (top left), medium (top right), and hard (bottom middle) difficulty for electrode Fz, generated via BrainVision Analyzer (n.d.), in the second experiment. Activity from 4 Hz to 20 Hz is displayed. The chosen baseline period was -500 ms to -100 ms and depicted activity is scaled from -10% (blue) up to 250% (red).

The topographies generated by the wavelet analyses shown in Figure 23 depict notable theta activity for all difficulties along at the frontal midline, particularly at Fz, after the presentation of a conclusion for the second experiment. Especially in the higher difficulties, there is clear frontal midline theta rhythm, which persists for the majority of the time windows. Universally, theta activity is more widespread for the 2,800 ms time window, being observable in frontal, anterior, and temporal regions.

Figure 23

Topographies generated by the wavelet analyses for the second experiment



Note. The topographies depict the easy (top), medium (middle), and hard (bottom) difficulty for electrode Fz, generated via BrainVision Analyzer (n.d.), for the midpoints of the time windows chosen for analysis in the second experiment. Activity at 5.27 Hz is displayed. Depicted activity is scaled from -10% (blue) up to 250% (red).

Discussion

The objective of this second experiment was to validate nonverbal syllogisms as a tool for measuring spatial reasoning abilities, another important aspect of fluid intelligence. This objective was pursued by testing whether nonverbal syllogisms constructed like spatial reasoning tasks would produce data in line with the initial predictions, which were formulated based on prior research into fluid intelligence. Much like the first experiment, the findings fell mostly in line with the general prediction. Again, it will be noted here how the findings related to the predictions, while more in-depth discussion will be held in the general discussion below.

Firstly, a moderate correlation between participants' RAPM score and their mean sensitivity could be determined in this second experiment. Consequently, participants that scored highly on the RAPM also had some chance at being better able to correctly evaluate nonverbal syllogisms, which falls in line with initial predictions. Also supporting the general predictions, participants' sensitivity and reaction time decreased as difficulty increased. Interestingly, there was no improvement in participants' sensitivity of correctly evaluating correct nonverbal syllogisms in the second half of the experiment. The first experiment showed clear improvements in in both sensitivity and reaction times, but for the second, only reaction times improved.

Similar trends as for the behavioural data were found for the ERS/ERD, again partially supporting the initial predictions. Theta power notably increased as difficulty increased, however this was again only the case for the middle and upper theta bands. It must be noted that the medium and hard difficulties differ from the easy difficulty, but not from one another. Such was the case for both the middle and upper theta band. For the most part, synchronisation was highest for Fz, however, there was a curious deviation in the lower theta band as it was found that activity was greater at both Fz and F1 as when compared F2. While there were no differences in activity between Fz and F1, this nonetheless implies that activity was greater in the left hemisphere as compared to the right. Lastly, no correlations were found between participants' mean sensitivity in correctly evaluating nonverbal syllogisms and their respective mean synchronisation for any of the theta bands, which runs counter to the initial predictions. Consequently, there appears no relation between performance and the theta activity exhibited.

General Discussion

The central problem that was noted was that while traditional syllogisms are very useful and widespread in the testing of fluid intelligence, they have serious, well-recorded issues due to their verbal nature. This research attempted to show that nonverbal syllogisms may serve as a solution to this problem by demonstrating their validity as a measure for testing fluid intelligence and its aspects, both behaviourally and physiologically, via testing a number of general predictions in two experiments. By and large, the results of the two experiments supported the viability of nonverbal syllogisms as a psychological testing tool, since the predictions were supported, albeit at times not fully. The findings and their relation to the predictions were only minimally remarked upon previously, for the sake of brevity, but will now be discussed in-depth.

The first argument for the validity of nonverbal syllogisms as measures of fluid intelligence is that participants' sensitivity in evaluating nonverbal syllogisms and their scores in the RAPM were correlated in both experiments. While not a high correlation in either case, this is in fact a positive, as the RAPM and the nonverbal syllogisms in the first and second experiment measure distinctly different aspects of fluid intelligence, and a high correlation would imply they are testing the same property in participants. The RAPM primarily measures abstract and analytical reasoning (Raven et al., 1998), while nonverbal syllogisms primarily measured visual working memory in the first experiment and spatial reasoning in the second. Although all these properties have been associated with fluid intelligence, they nevertheless are distinct and employ different processes in their operation (Goodwin, 2015; Kyllonen & Christal, 1990; Lohman, 1996). These distinctions would explain why the correlations were only moderate in nature. Nevertheless, the correlation between a well-regarded test for fluid intelligence and these two types of nonverbal syllogisms serves as initial validation of the latter's ability to test attributes associated with fluid intelligence.

Beyond the correlations with the RAPM, in both experiments participants' sensitivity and reaction times decreased as difficulty increased, much like initially predicted. However, there were curious trends when comparing the behavioural data for both experiments. In the first experiment, the differences between participants' sensitivity and reaction times due to the difficulty were far less pronounced as when compared to the second experiment. Specifically, while there were sizable differences when comparing the behavioural data of the easy difficulty to either the medium or hard difficulty in the first experiment, the medium and hard difficulties were far less distinct from one another, and reaction times did not differ at all between them. Meanwhile, in the second experiment there was an almost linear decrease per difficulty for both sensitivity and reaction time, rather than the sharp drop in both which was the case in the first experiment.

These differences can perhaps best be described as arising due to the capacity of working memory and the construction of the nonverbal syllogisms in this first experiment. Cowan (2010) argued that a central limit of four items can be maintained at one time within one's memory. More specifically, as individuals encounter information they must retain, they will attempt to transform it into distinct items, chunks, which they will keep accessible within their working memory. In the case of first experiment, premises likely formed such chunks, as they required participants to memorize the exact positioning of geometric figures. Furthermore, with at most four premises to memorize, the encoded information should not have exceeded this noted working memory limit. However, participants may have needed additional memorization due to how conclusions were hidden two and half seconds after they were first revealed. These further memorization demands proved to cause little issue in the easy difficulty, as participants only had to memorize two premises at a time. However, in the medium and high difficulties, having to memorize the premises and then also the longer geometric sequences which made up the conclusions overburdened working memory to the point that performance suffered. This would explain the far smaller, and lack of, differences between the behavioural data for these higher difficulties in the first experiment. The behavioural data of the second experiment, which exhibited a more consistent decrease in sensitivity and reaction time, lends further credence to the idea that hiding the conclusions in the first experiment resulted in overburdening the participant, potentially causing them to guess as they were unable to memorize the conclusion in time.

Additionally, there were differences between the experiments in how the participant improved over the course of the session. In the first experiment, the findings clearly showed that participants improved in their performance, as they showed both higher sensitivity in correctly evaluating nonverbal syllogisms and higher reaction times in the second half of the experiment as compared to the first, albeit only for the easy and medium difficulty. The most likely cause of this improvement in performance is that participants continuously refined their strategies in encoding and retaining the information given by the premises, and potentially even their strategies to retain the conclusion partially or fully. Such improvement would fall in line with other working memory experiments such as those performed by McNamara and Scott (2001), where the strategic use of working memory led to improved performance by participants. However, this does not explain why there was no improvement in the hard difficulty. Perhaps the best explanation is that it was not possible for participants to improve at this level of difficulty because they were already too overburdened by the memorization demands. As they were unable to fully memorize everything they needed to, they could not form a cohesive strategy which could be improved upon.

Curiously, this lack of improvement is replicated to some degree in the second experiment. While reaction times showed clear improvement over the course of the second experiment, there was no change to participants' sensitivity of correctly evaluating nonverbal syllogisms in the latter half of the session. A potential interpretation of the findings was that while participants became more familiar with the task itself, they did not find ways to improve their strategies to resolve the challenges of the tasks, or alternatively, that the overall process they employed to evaluate the nonverbal syllogisms remained the same. This runs counter to other research into spatial ability, as it has been noted that spatial ability is perhaps the aspect of fluid intelligence most affected by practice (Lohman, 1993; Lohman, 1996; Lohman & Nichols, 1990).

Regarding the ERS and ERD, theta power notably increased with difficulty in both experiments, however this was only the case for middle and upper theta bands. A curious finding in the first experiment was that the upper theta bands had different levels of theta power for each difficulty, while for middle theta there were only differences when comparing the easy difficulty with either the medium or hard difficulty. These findings, especially for the ones found in the upper theta band, lined up with prior research which showed clear trends of theta activity emerging as working memory is burdened, and that this activity increased the greater the burden (Klimesch et al., 1996; Maurer et al., 2015; Sauseng et al., 2010). Additionally, the findings provided further evidence for the theory that increases in theta power at the frontal midline are associated with short-term memory demands (Klimesch, 1996; Klimesch et al., 1996).

However, these prior studies did not provide an explanation for why, in the second experiment, the medium and hard difficulties differed from the easy difficulty, but not from one another. Such was the case for both the middle and upper theta band. This, as well as the fact that there was no learning effect in the second experiment can perhaps best be explained by the study performed by Byrne and Johnson-Laird (1989) in which they investigated spatial reasoning. They performed two experiments employing three term series problems, tasks not too dissimilar to verbal syllogisms, to determine whether the number of mental models of spatial relations individuals had to form influenced their ability to solve said problems. What they found was that individuals consistently had performed better when they only had to form a single model, rather than multiple (Byrne & Johnson-Laird, 1989). These findings would explain the strange findings for sensitivity over time and theta power increases. For the easy difficulty, the two premises were always related, as they shared one geometric figure. Consequently, participants were naturally able to form a single model containing all the spatial relations given by the premises. However, for the medium and high difficulties, premises that did not form indirect relations could be presented alongside the two related premises. The result was that theta power did not differ for the medium and hard difficulty as participants struggled to construct and maintain multiple, simultaneous models describing the spatial relations given by the premises. To put it in other words, it was misunderstood how to increase the workload of the nonverbal syllogisms when they were designed to test spatial reasoning. It was not the addition of more premises that increased demands placed upon the participant, but rather the need to create additional models. This would also explain why there was no improvement in the second half. While the literature argues that individuals get better at spatial ability tasks with more practice, the nonverbal syllogisms did not serve as sufficient practice. The greatest difficulty in this experiment was the construction and maintenance of mental models formed by the premises, whereas in the first experiment, it was the effective encoding and retrieval of the premises for each conclusion. As there were only 30 sets of premises in each experiment, but 300 conclusions, it stands to reason that participants in the first experiment can be considered as having received more practice, a fact that is reflected by the fact that a noticeable improvement can be detected in the second half of the experiment.

Finally, it was predicted that activity would be highest at the frontal midline and indeed, Fz, or rather the frontal midline, was clearly the centre of activity in both experiments. This coincides with results from prior research, which found just such a trend. For instance, Gevins et al. (1997) found increases in theta activity along the frontal midline when employing continuous matching tasks, and further noted that this increase in activity corresponded to an increase in memory load. His was not the only study that found a theta rhythm specifically along frontal midline when performing experiments on working memory (Itthipuripat et al., 2013; Klimesch, 1996). Naturally, theta activity emerging along the regions overlaying the prefrontal cortex has previously been noted when operations involving spatial ability are performed, as well (Duncan et al., 2000).

It must also be noted that in the lower theta band it was found that activity was greater at Fz and F1 than F2. In other words, activity was greater in the left hemisphere as compared to the right. This is not an entirely novel finding, as Moen et al. (2020) found that participants working on mental rotation skills would generate activity over the left dorsolateral prefrontal cortex. However, this does imply that the locations that were analysed for this second experiment may not have been the best options to pick up activity generated by participants evaluating nonverbal syllogisms which required spatial reasoning.

Regardless of whether the single occurrence of power in the lower theta band being greater in the left brain hemisphere implied its greater involvement in fluid intelligent operation, by and large, both experiments reinforced the assumption that lower theta was only minimally representative of the demands placed upon fluid intelligence by nonverbal syllogisms. Whether nonverbal syllogisms were constructed in such a way that they focused on testing working memory or spatial reasoning, no differences were found for the different difficulties at lower theta. While this lack of any differences among the difficulties in the lower theta band and the limited effects found for middle theta, at least in the first experiment, were curious, they were not extremely unusual. Both the lower and middle theta bands have previously been associated with motor preparation and imagery (Van der Lubbe, 2021). Any continuous activity in the lower theta band as such likely had a different source, such as perhaps attention maintenance, the planning of a motor action, or perhaps the maintenance of relevant information, like mental models depicting the relations between geometric figures given by the premises (Hsieh & Ranganath, 2014). Lower theta being representative of maintaining information would certainly explain why there was a correlation found between participants mean sensitivity and their mean synchronisation in the first experiment, as participants that had higher sensitivity would also have had to be better at maintaining memorized information.

There exist some last trends that have not previously been addressed, as they did not relate to the initial predictions. The first such trend is the consistent and extreme increase in theta activity compared to the baseline that occurred towards the end of the chosen 4,000 ms segments. In the first experiment, the beginning of this burst in activity materialized almost exactly at the same time as conclusions were hidden after 2,500 ms, whereas in the second experiment it only appeared shortly before 3,000 ms had passed since the presentation of a conclusion. The fact that the emergence of these bursts coincided so neatly with the hiding of the conclusion in the first experiment but began later in the second experiment, makes it likely that this was largely related to motor processes. Participants at those times began to either plan or execute their response. It is unlikely that such a big increase in activity would emerge so suddenly when participants have been engaging with the same stimulus for quite some time before it emerged. Furthermore, the activity emerges quite close to the calculated means for reaction time, especially for the first experiment, which coincidentally also had what appeared as a bigger burst in theta activity across all theta bands. This further supports the theory that this increase in theta power was due to the mental processes involved in motor activity.

The second trend is the continuous activity in the lower theta range in the second experiment. In the first experiment there is an initial burst of activity, followed by activity returning closer to baseline until it increases shortly after again. This also occurs in the second experiment, however only for the upper theta ranges. There appears continuous theta activity in along the lower theta ranges. A potential explanation for this could be the need for participants to actively maintain their mental model. In the first experiment individuals only had to retrieve chunks, consequently there was less need for the active maintenance that the second experiment demanded in needing participants to retain their mental representations of the relations between geometric figures. It would also explain why this activity appears so visually similar between the medium and hard difficulty in the second experiment. As participants largely had to maintain at least one more mental model, there was a subsequent increase in the theta activity they generated.

Limitations and future research

There were two major methodical limitations to this research. The first is that the conclusion was hidden in the first experiment. While participants' behavioural data still differed across conditions, the differences are much less pronounced than in the second experiment, where no conclusions were hidden. As such, it is likely that some nuance was lost by endeavouring to create a period where participants would not engage in motor preparation or execution. Furthermore, hiding the conclusion might have added greater demands upon working memory based upon the complexity of the conclusion that was hidden, thereby resulting in theta activity that was less representative of the different difficulties.

The second major methodical limitation was the absence of a period within which participants were not allowed to answer in the second experiment. Due to the increased difficulty of spatial manipulation, conclusions were neither hidden, nor were participants restricted on when they could give their answer. This proved to be disadvantageous in the later analysis and interpretation of the results. While the behavioural data suggests average reaction times ranged from three to five seconds, and responses made within one second after a conclusion was shown were excluded for the wavelet analyses, there remained trials in which participants answered very quickly. Consequently, it is possible that the investigated theta activity in the second experiment could have been influenced by other processes, such as motor preparation and activation, especially in the lower and middle theta bands (Van der Lubbe et al., 2021).

As a result of both these limitations, there is some question of how representative the recorded theta activity is of working memory activity in the first experiment and spatial reasoning in the second experiment. Future studies may wish to implement a period within which participants cannot answer, to better investigate the mechanism of solving nonverbal syllogism and its potential in measuring fluid intelligence. And further, if spatial reasoning is being investigates as in the second experiment, it may prove fruitful to also allow the participants to view the conclusions at the same time as the conclusion. This could result in activity that is truly reduced to just the spatial reasoning processes, as there are less immediate and overarching memorization demands. Of course, this would make no sense for studies attempting to utilize nonverbal syllogisms to investigate working memory, in which premises should indeed be hidden while the participant is evaluating conclusions. However, working memory loads may be better monitored by not hiding the conclusion, as participants would have no need for additional memorization beyond that of the premises.

Another less critical limitation could be the fact that the utilized stimuli differed on multiple dimensions. Participants noted in discussion with the researcher that they employed different strategies, primarily focused on either shape or colour. Future research may find it fruitful to restrict the stimuli used to construct nonverbal syllogisms down to only one difference, such as only using differing shapes but the same colour, or different colours while retaining the same shape.

It must also be noted that the statistical analysis was quite restricted, only investigating Fz, F1, F2. While these electrodes showed high activity and were placed centrally along the frontal midline, which has previously been identified as being quite important for operations associated with fluid intelligence, potentially other relevant trends were not revealed on account of this rather restricted approach. For the two experiments of this study, it proved sufficient to explore the viability of nonverbal syllogisms as a method for testing fluid intelligence via its aspects of working memory and spatial reasoning. Future research may wish to conduct more exhaustive analyses, to further determine the potential of nonverbal syllogisms and the behavioural and physiological data solving them can generate.

Lastly, the participants in both experiments were drawn from a notably homogenous group. Namely, all participants were younger adults and further, as recruitment was conducted via SONA, all participants were at the time of the research, or had been previously, students at the University of Twente. This is relevant because fluid intelligence has been found to primarily peak in early adulthood and decline with age (Horn & Cattell, 1967). Furthermore, as university students, it is likely that participants had a somewhat higher baseline for fluid intelligence, as it has been noted that fluid intelligence can be trained and that this training is to some degree transferable to other tasks (Jaeggi et al., 2008; Sternberg, 2008). Consequently, participants likely performed on a different level as compared to a sample drawn from a more diverse group. Future research on nonverbal syllogisms may seek to broaden their recruitment to include participants of different ages and education levels.

Practical implications

The first experiment adds further support to an already respectable body of evidence regarding the effects of frontal midline theta activity and how it relates to working memory operation (Ishihara & Yoshii, 1972; Jensen & Tesche, 2002; Klimesch et al., 1996; Maurer et al., 2015; Qiu et al., 2009; Roberts et al., 2013). For the second experiment, distinct activity at the frontal midline was found in the process of testing spatial reasoning, which supports prior findings that theta activity and the prefrontal cortex is involved with processes that demand spatial ability (Gevins et al., 1997; Itthipuripat et al., 2013). Most importantly, however, both experiments show that nonverbal syllogisms can serve as a valuable potential tool for measuring various aspects of fluid intelligence. At this moment, only working memory and spatial reasoning have been explored with them, but the flexibility in their construction and their benefits compared to verbal syllogisms are strong arguments in their favour. While further research is needed to understand the specifics of how to best use nonverbal syllogisms as a measure, this study serves as an important first step in attempting to implement them.

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Appendix A: Informed consent

Welcome to this experiment!

Title of this research

The involvement of the prefrontal cortex while solving nonverbal syllogisms

Background and purpose of this study

Past research conducted at the University of Twente measured event-related potentials while subjects worked on solving nonverbal syllogisms constructed from different arrangements of geometric figures and has observed a late negativity over frontal brain areas. It has been proposed that this frontal negativity may be an indicator of fluid intelligence, which describes the ability to think abstractly and reason effectively with new information. However, more research is needed to investigate this, which this research aims to provide.

Procedure

This study consists of one (1) session that will not take more than 240 minutes (4 hours). You must be at least 18 years of age to participate.

This experiment consists of two parts. In the first part, you will be presented with the Raven Advanced Progressive Matrices (RAPM) test, wherein you will be given several geometric figures arranged in a pattern and be asked to fill the missing space in a way that will complete the pattern. This part of the experiment will take 40 to 60 minutes.

Afterwards, in the second part, you will have your brain activity measured via EEG, as you work on a large number of nonverbal syllogisms. These nonverbal syllogisms will consist of premises and conclusions constructed from differently coloured geometric shapes, and you will need to judge whether a conclusion adheres to the given premises. You will face three sets of nonverbal syllogisms in total, with each set having a different number of premises, namely two premises, three premises, or four premises.

Potential risks

The participants face no known risks as a consequence of their participation. Furthermore, participating in this experiment is entirely voluntary, and you have the right to withdraw from it at any time. All data collected over the course of this experiment will be treated as confidential, and made anonymous, so it cannot be used to identify you in the case any part of this research is publicized.

Potential benefits

Participation in this experiment is not expected to significantly benefit the participants. However, if you have arranged your participation via the Test Subject Pool system (SONA) you will be credited 4.5 points upon completion of the experiment.

Questions

In the case of any questions regarding this research, please contact the researcher, Tobias Merkelbach, via t.m.merkelbach@student.utwente.nl.

Concerns

In the case of concerns or complaints with the research, please contact the Faculty of Behavioural, Management and Social Sciences at the University of Twente, via ethicscommittee-bms@utwente.nl.

By consenting to participate, you acknowledge that you are voluntarily taking part in this experiment, are aware you can withdraw consent and end your participation whenever you want, and that you are at least 18 years old.

Signature: ______________________ Date: ______________________

Appendix B: Pre-session instructions

Experiment 1

Dear Participant,

Thank you very much for signing up for this study!

As an EEG study, there are some things that you can do before the experiment to improve the quality of the recorded data.

1. Please shower and wash your hair the night before or in the morning of the experiment, as clean hair is needed to get good EEG signals.
    - In the case that your hair is still wet when you arrive, you may need to use the blow dryer in the lab room to dry your hair.
2. Please avoid consuming caffeinated food and drinks (coffee, etc.) for up to 8 hours before the experiment.
3. Try to get a good night of sleep before the day of the experiment.
4. If you use sight correction, such as glasses or contacts, please take glasses with you to the experiment. This will make it easier to record good data.
5. If you wear makeup, parts of it may need to be reapplied after the end of the experiment, as it is necessary to attach electrodes around the eyes.

Should you have any questions or concerns, please do not hesitate to contact t.m.merkelbach@student.utwente.nl.

Kind regards,
Tobias Merkelbach

Experiment 2

Dear Participant,

Thank you very much for signing up for this study!

As an EEG study, there are some things that you can do before the experiment to improve the quality of the recorded data.

1. Please shower and wash your hair the night before or in the morning of the experiment, as clean hair is needed to get good EEG signals.
2. Please avoid consuming caffeinated food and drinks (coffee, etc.) for up to 2-3 hours before the experiment.
3. Please avoid consuming alcohol the day before and up to the experiment.
4. Try to get a good night of sleep before the day of the experiment.
5. **If you require seeing aids, please take glasses, not contact lenses, with you to the experiment.**
6. If you wear makeup, parts of it may need to be reapplied after the end of the experiment, as it is necessary to attach electrodes around the eyes.

Should you have any questions or concerns, please do not hesitate to contact t.m.merkelbach@student.utwente.nl.

Kind regards,
Tobias Merkelbach

Appendix C: EEG questionnaires for inclusion/exclusion of participants

Experiment 1

Do you have electrical devices within your body? (Pacemaker, hearing aid, etc.)

- Yes
- No

Do you regularly take medication?

- Yes
- No

Have you taken medication today?

- Yes
- No

Do you regularly consume alcohol and/or drugs?

- Yes
- No

Have you consumed alcohol and/or drugs today?

- Yes
- No

Have you consumed coffee today?

- Yes
- No

Do you have a sleeping disorder?

- Yes
- No

Are you currently lacking sleep? (less than 8 hours of sleep)

- Yes
- No

Do you have a diagnosed neurological or psychiatric disorder?

- Yes
- No

Do you have a diagnosed learning disorder?

- Yes
- No

Do you require seeing aids? (Glasses, contact lenses, etc.)

- Yes
- No

Have you showered before the experiment?

- Yes
- No

Have you used any beauty products today? (Hair gel, make-up, etc.)

- Yes
- No

Experiment 2

Do you have electrical devices within your body? (Pacemaker, hearing aid, etc.)

- Yes
- No

Do you regularly take medication?

- Yes
- No

Have you taken medication today?

- Yes
- No

Do you regularly consume alcohol and/or drugs?

- Yes
- No

Have you consumed alcohol and/or drugs today or yesterday?

- Yes
- No

Have you consumed coffee up to 3 hours before the experiment?

- Yes

- No

Do you have a sleeping disorder?

- Yes
- No

Do you believe you are currently lacking sleep?

- Yes
- No

Do you have a diagnosed neurological or psychiatric disorder?

- Yes
- No

Do you have a diagnosed learning disorder?

- Yes
- No

Do you require seeing aids? (Glasses, contact lenses, etc.)

- Yes
- No

Did you wash your hair before the experiment?

- Yes
- No

Have you used any beauty products today? (Hair gel, make-up, etc.)

- Yes
- No

Appendix D: Block order

Table D1

Sequence of easy, medium, and hard blocks for the orders employed in both experiments

		Difficulty					
		1st block	2nd block	3rd block	4th block	5th block	6th block
Order	A	Easy	Medium	Hard	Easy	Medium	Hard
	B	Medium	Hard	Easy	Medium	Hard	Easy
	C	Hard	Easy	Medium	Hard	Easy	Medium
	D	Easy	Hard	Medium	Easy	Hard	Medium
	E	Medium	Easy	Hard	Medium	Easy	Hard
	F	Hard	Medium	Easy	Hard	Medium	Easy

Appendix E: Experiment instructions

Experiment 1

Instructions in the first experiment were a mixture of written and spoken. Participants received visual examples of premises and conclusions, with basic written explanations for why they were correct or incorrect, as well as more elaborate spoken explanation for better comprehension.

Nonverbal Syllogisms - Instructions

What is a nonverbal syllogism?

- Nonverbal syllogisms are logic problems, consisting of a set of premises and a conclusion
- You must determine if a conclusion is correct or incorrect based on the given premises

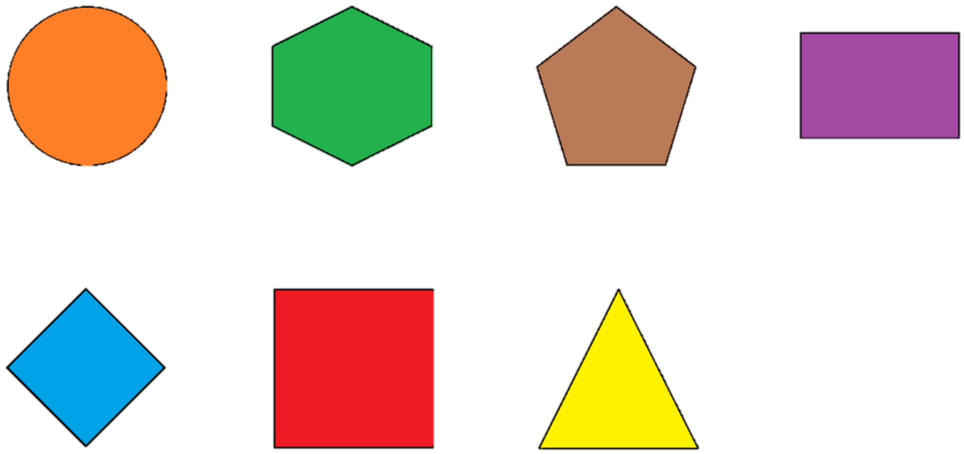
What form do these nonverbal syllogisms take?

- All elements of nonverbal syllogisms are constructed from geometric figures
    - Premises contain **2** figures
    - Conclusions contain **4** figures

How to determine whether a conclusion is correct or incorrect?

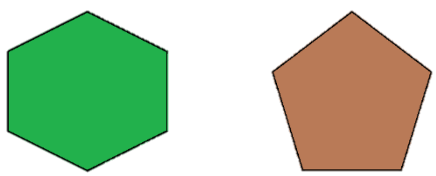
- **A conclusion is incorrect only if the geometric figures are not shown in the order they were presented in the premises**
- To make this clearer, there are two pages with examples, one for correct conclusions and one for incorrect ones, as well as explanations for why they are as such
- There is also one page for when multiple premises use the same figure

The geometric figures used to construct the nonverbal syllogisms

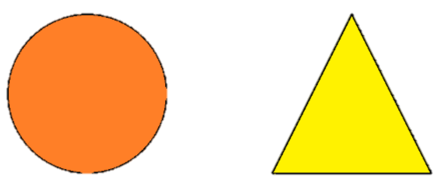


Examples for CORRECT nonverbal syllogisms

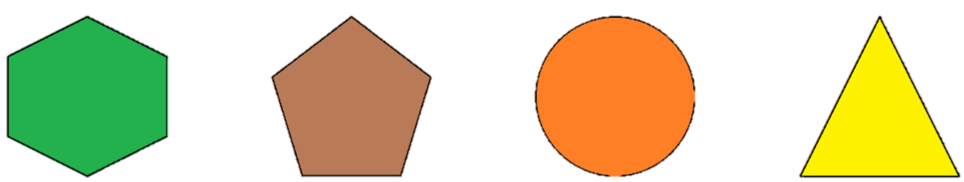
Premise 1



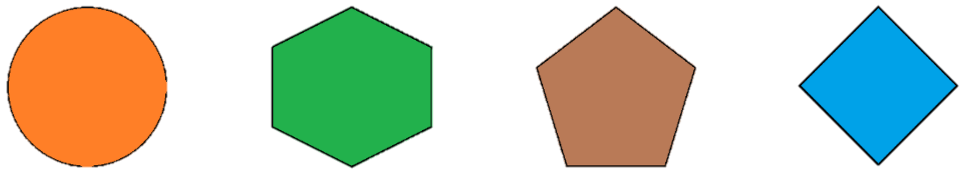
Premise 2



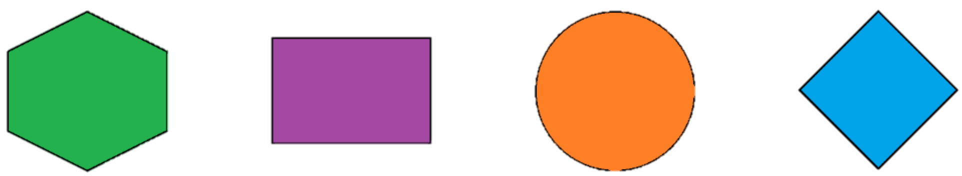
Conclusion



Explanation: Both premises are shown, with the figures arranged in the same order as in the premises.



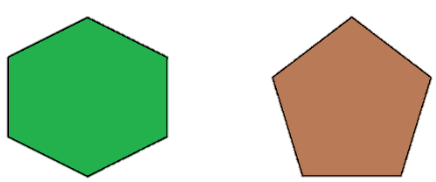
Explanation: Only one full premise is shown, but it remains in the order depicted in the premise. The circle is there, but without the triangle it is associated with appearing, it is merely another filler figure for the conclusion.



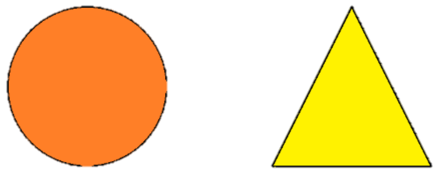
Explanation: some of the figures shown in the premises are there, but they are not followed by the other figure they are associated with, and as such the order presented in the premises is not broken.

Examples for INCORRECT nonverbal syllogisms

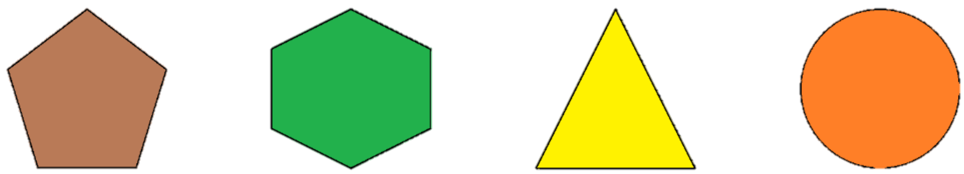
Premise 1



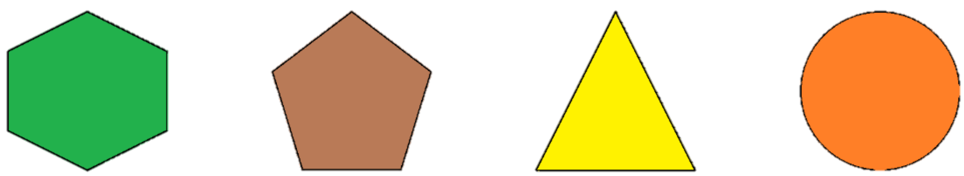
Premise 2



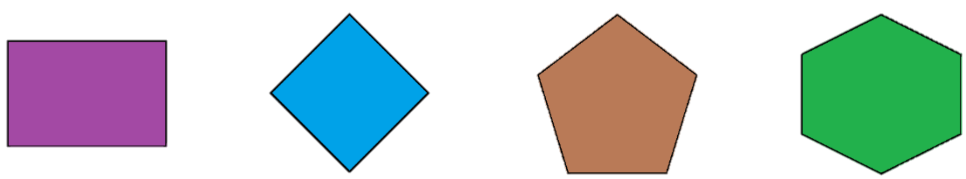
Conclusion



Explanation: The order depicted in the premises is broken for both sets of figures.



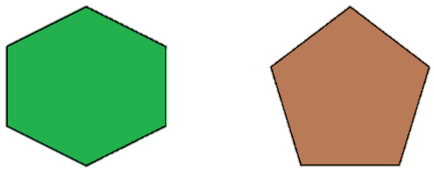
Explanation: While one pair of figures is shown as depicted in the premises, the other has its order reversed.



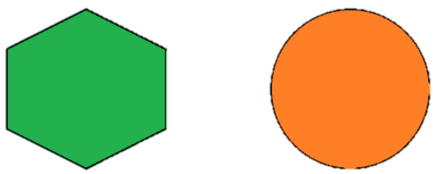
Explanation: Only one set of the figures depicted in the premises appears here, but it does not have the same order as was originally depicted.

Examples for nonverbal syllogisms with premises using the SAME figures

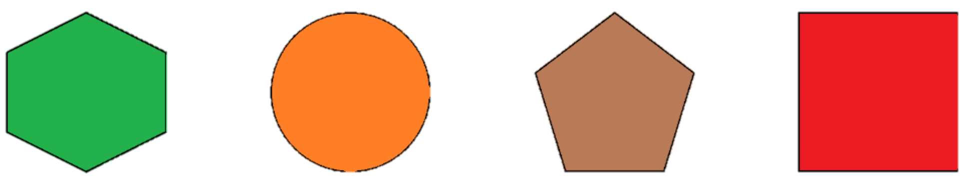
Premise 1



Premise 2

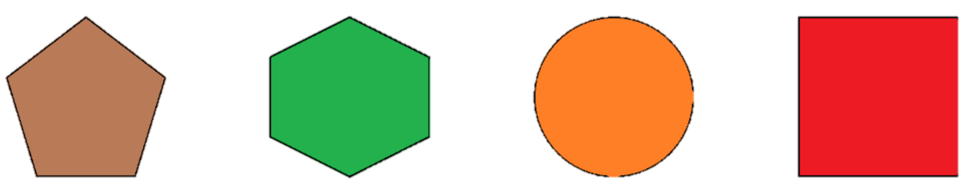


Conclusions (CORRECT)



Explanation: While all figures in used in the premises are present, technically only one premise is depicted here, hexagon and circle, and the order of this premise is not broken.

Conclusion (INCORRECT)



Explanation: While one premise is shown in the correct order, the other set of figures is reversed to what is shown in the premises.

Example of a trial with 2 premises in the experiment

- Each line means a new screen is shown for the next section
- A fixation cross will be presented before each premise and conclusion, to allow the participant to focus on the middle of the screen

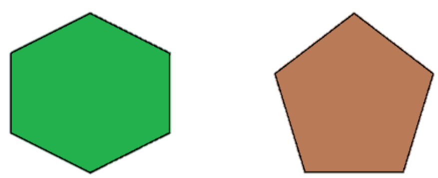
---

Now, new premises will be given.

Press the UP button when ready.

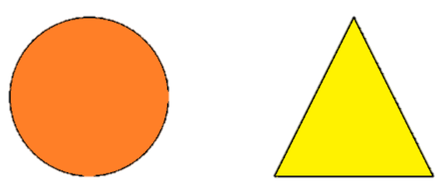
+

Premise



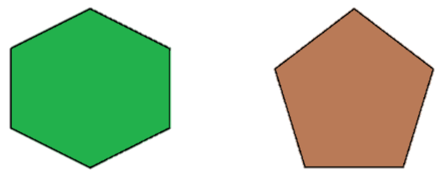
Premise

+



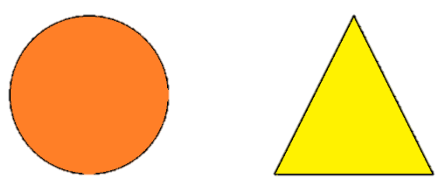
Premise

+



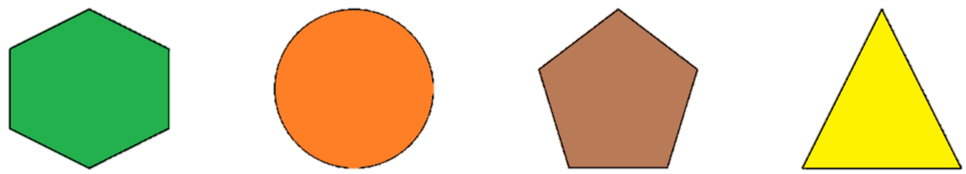
Premise

+



Conclusion

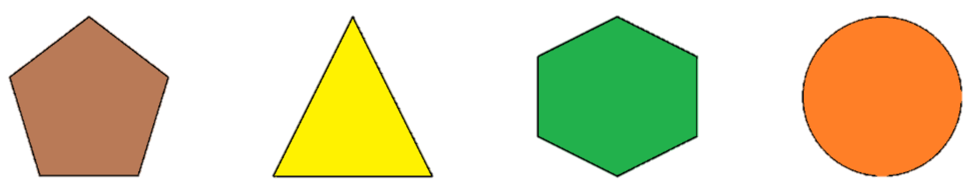
+



?

Conclusion

+



?

And so on...

Experiment 2

Instructions in the second experiment included far more visual examples of nonverbal syllogisms, with only minimal written explanations, as it appeared that spoken discussion regarding what made conclusions correct or incorrect facilitated understanding more effectively. The example syllogism for each difficulty contained a correct and incorrect version for each of each type of conclusion. Conclusions 1 and 2 were direct conclusions, conclusions 3 and 4 were indirect conclusions, and conclusions 5 and 6 were simple conclusions. While not explicitly labelled, the current set of examples was constructed to give participants a good basic understanding of the different types of nonverbal syllogisms and prepare them for any they would encounter over the course of the experiment.

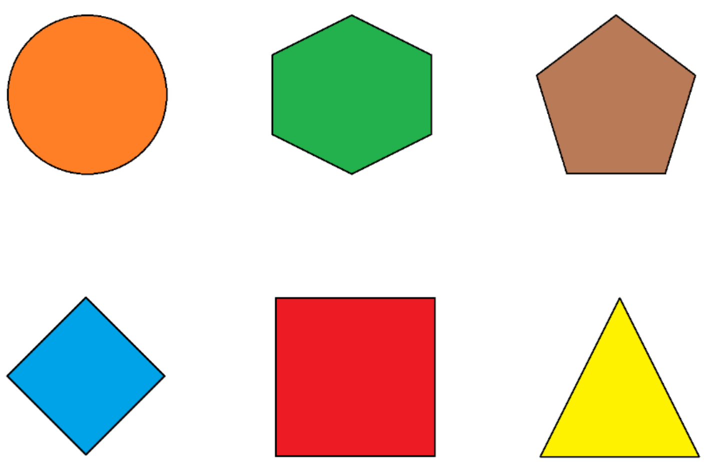
Nonverbal Syllogisms - Instructions

What is a nonverbal syllogism?

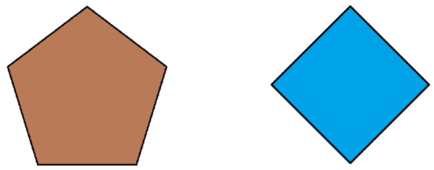
- Nonverbal syllogisms are logic problems, consisting of a set of premises and a conclusion
- You must determine if a conclusion is correct or incorrect based on the given premises

What form do these nonverbal syllogisms take?

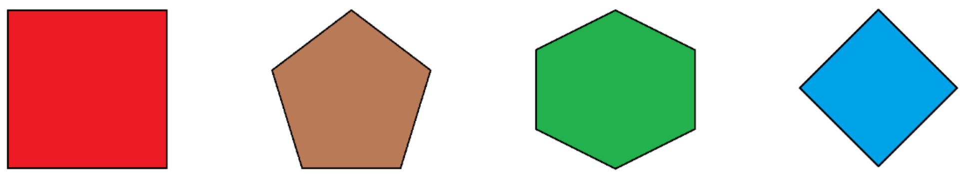
- All elements of nonverbal syllogisms are constructed from geometric figures
    - These are the only 7 figures you will see in this experiment (colours will not change)



- Premises contain **2** figures (example below)



- Conclusions contain **4** figures (example below)
    - This would be a correct conclusion based on the previous premise



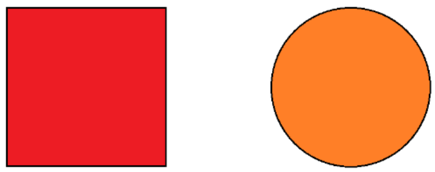
How to determine whether a conclusion is correct or incorrect?

- **A conclusion is incorrect if the geometric figures are not shown in the order they were presented in the premises**
- **This is the case for both direct and indirect relations established by premise (will be explained with examples)**
- To make this clearer, there are a few pages with examples, each including a set of premises, one correct conclusion and one incorrect, for different types of nonverbal syllogisms

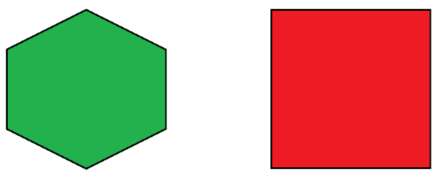
How will the experiment be structured?

- The experiment is divided into 6 blocks, each with 5 rounds
- Each round contains a new set of premises and 10 conclusions that must be evaluated based on these premises
- The number of premises given per round (2, 3, or 4) can vary between blocks
- You will be informed when the number of given premises changes
- Between each block, there will be a short pause where the EEG equipment will be checked
- An example of the start of a round will be given

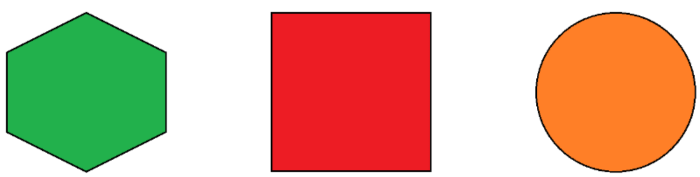
Examples (2 premises)
Premise 1



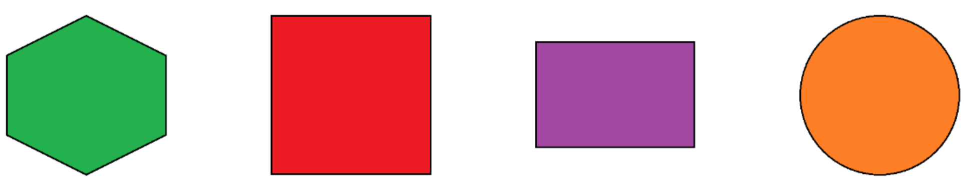
Premise 2



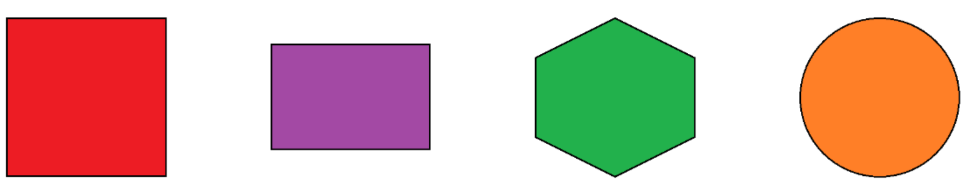
Relation (**this will not be shown in the experiment**)



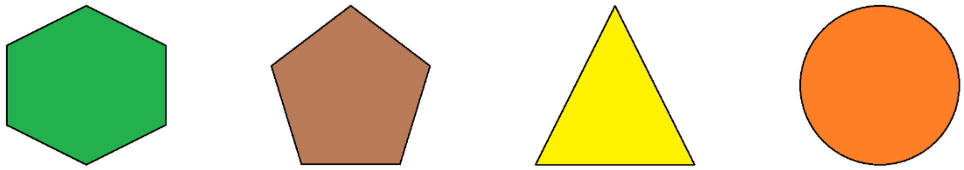
Conclusion (Correct)



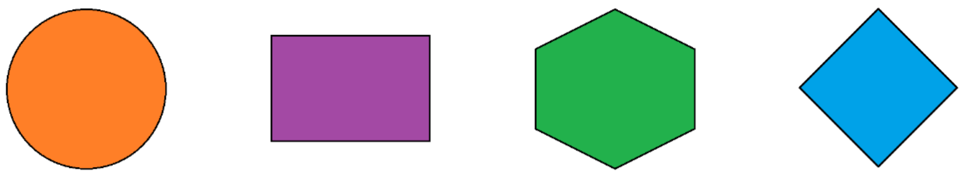
Conclusion (Incorrect)



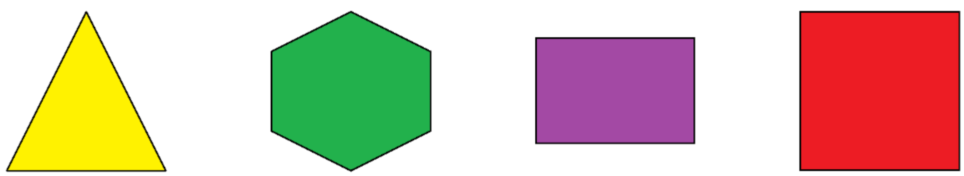
Conclusion (Correct)



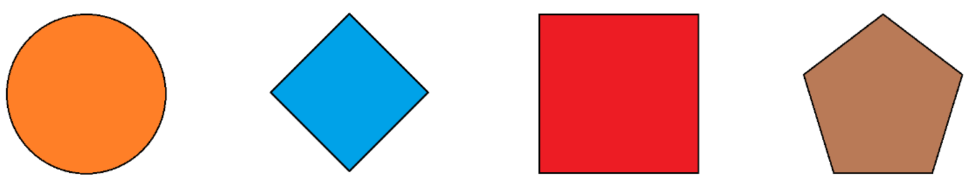
Conclusion (Incorrect)



Conclusion (Correct)

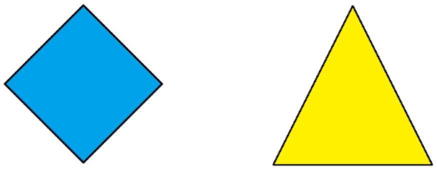


Conclusion (Incorrect)

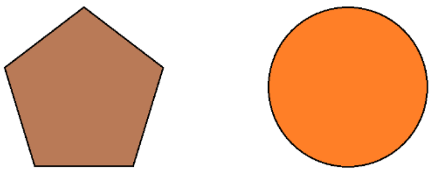


Examples (3 premises)

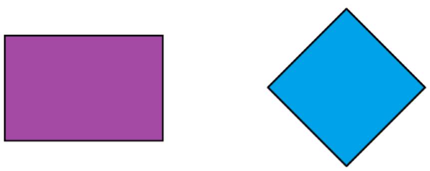
Premise 1



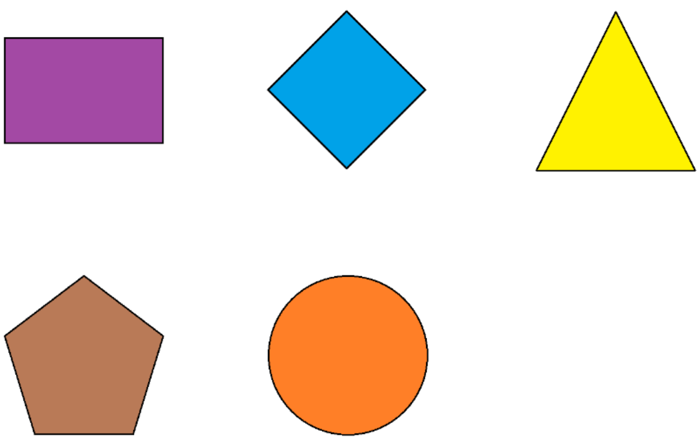
Premise 2



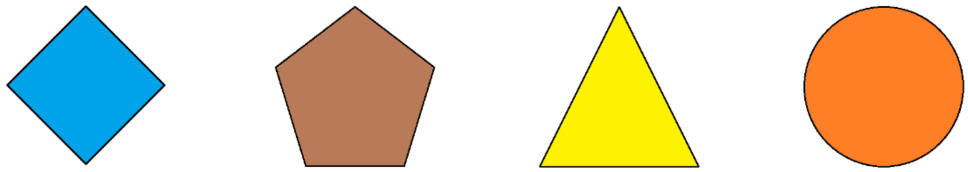
Premise 3



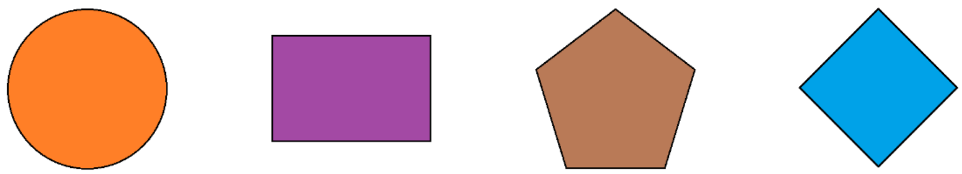
Relation (**this will not be shown in the experiment**)



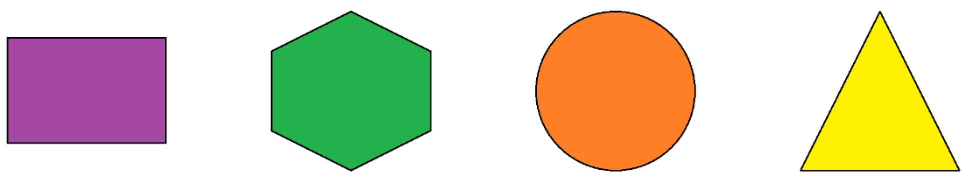
Conclusion (Correct)



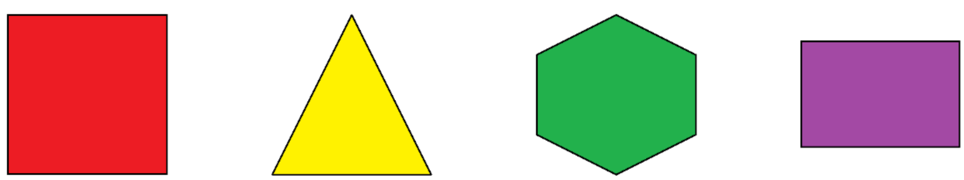
Conclusion (Incorrect)



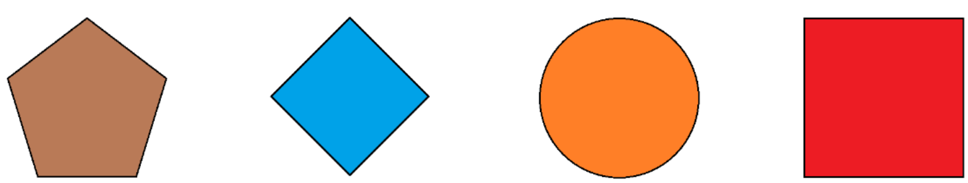
Conclusion (Correct)



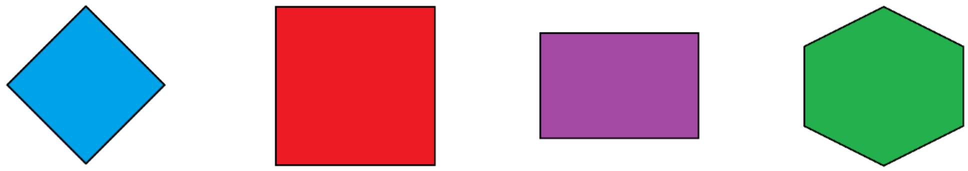
Conclusion (Incorrect)



Conclusion (Correct)

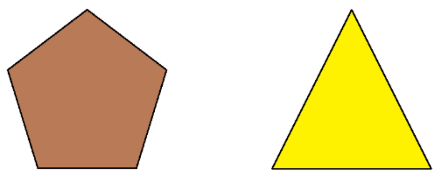


Conclusion (Incorrect)

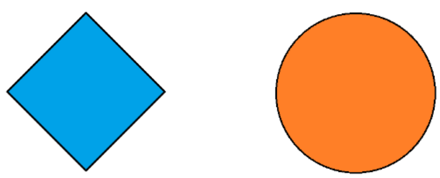


Examples (4 premises)

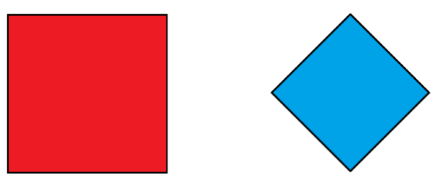
Premise 1



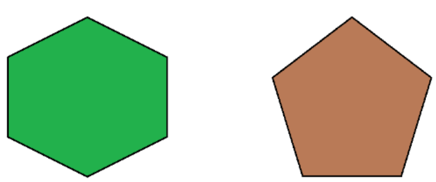
Premise 2



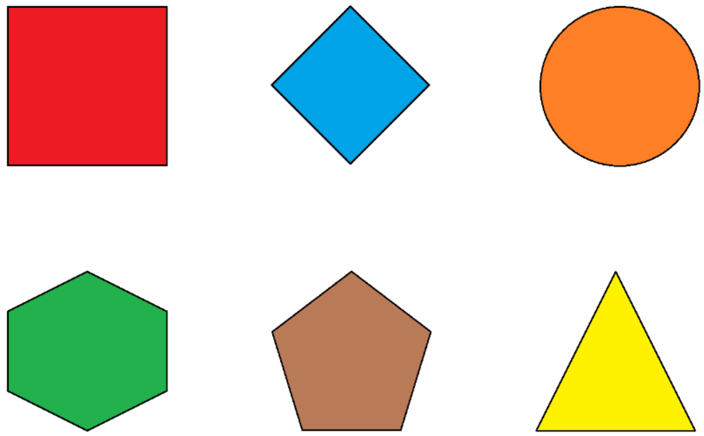
Premise 3



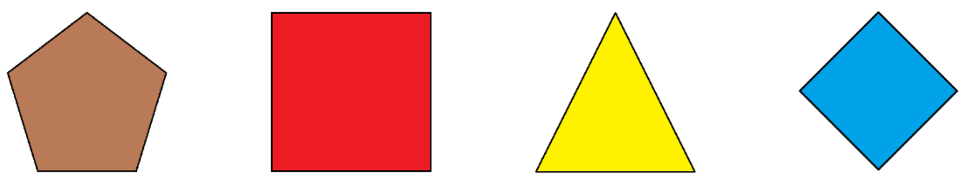
Premise 4



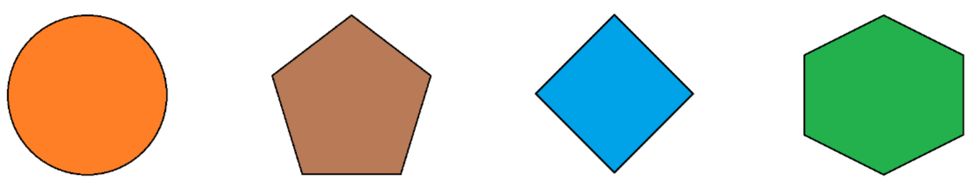
Relation (**this will not be shown in the experiment**)



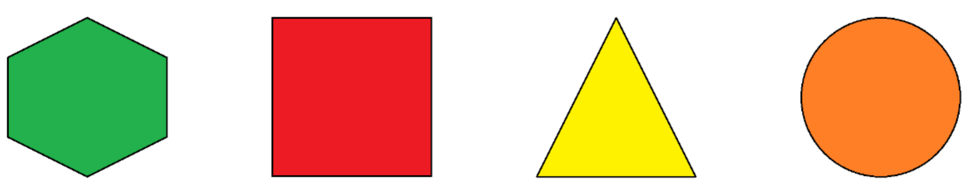
Conclusion (Correct)



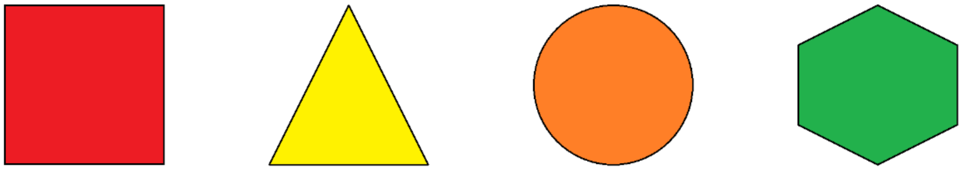
Conclusion (Incorrect)



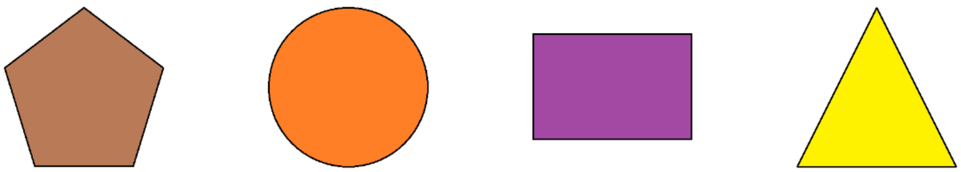
Conclusion (Correct)



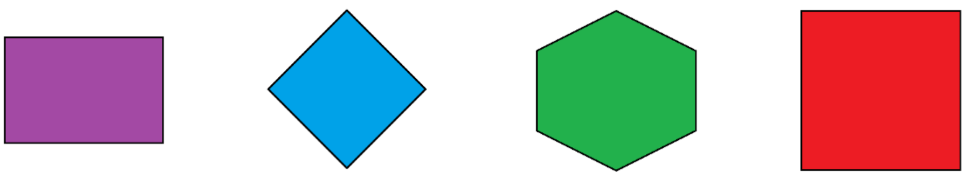
Conclusion (Incorrect)



Conclusion (Correct)



Conclusion (Incorrect)



Example of a trial with 2 premises in the experiment

- Each line means a new screen is shown for the next section
- A fixation cross will be presented before each premise and conclusion, to allow the participant to focus on the middle of the screen

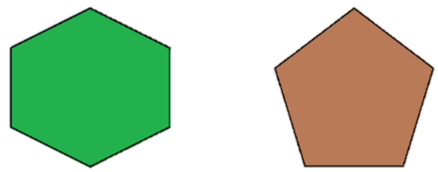
---

Now, new premises will be given.

Press the UP button when ready.

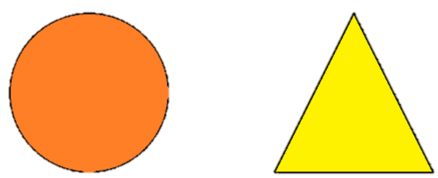
+

Premise



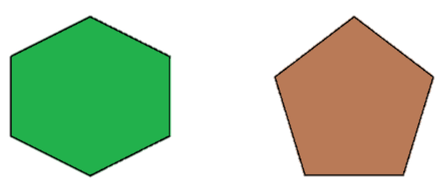
Premise

+



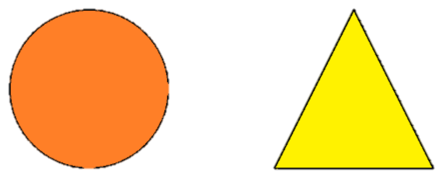
Premise

+



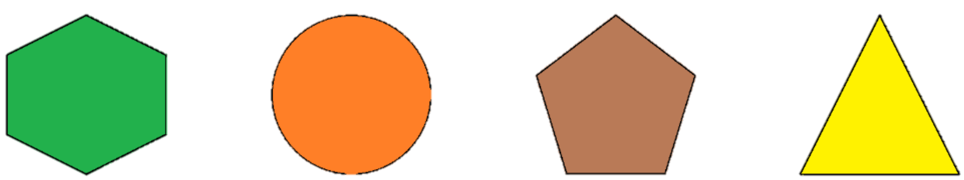
Premise

+



Conclusion

+



Conclusion

Appendix F: MATLAB code

Experiment 1

```
DataPath='C:\Users\Tobia\Documents\Psychology Master\Thesis\BrainVision
Analyzer\Nonverbal Syllogisms\Experiment 1\Experiment 1 Export\Raw Data Files';
npn=input('How many data files do you want to process? ');
vpn = 1;
for vpn = 1:npn
[fname,pname] = uigetfile([DataPath,'.raw']);  % asks for the filename to analyze
fid = fopen([pname fname],'r');
sample = 1; %duration of one sample
premature = 100; %the criterion in ms for too fast responses
button = [1 2]; % 1= left (correct), 2= right (incorrect)
fileline = 0;
trialnr = 0;
B1 = 0;
B2 = 0;
ID=[];
stim = [200 210 220 230 240 250 201 211 221 231 241 251];
% 200 correct 2 premises, 210 incorrect 2 premises all first half
% 220 correct 3 premises, 230 incorrect 3 premises all first half
% 240 correct 4 premises, 250 incorrect 4 premises all first half
% 201 correct 2 premises, 211 incorrect 2 premises all second half
% 221 correct 3 premises, 231 incorrect 3 premises all second half
% 241 correct 4 premises, 251 incorrect 4 premises all second half

response = 1;
data=[];
processed=[];
while fileline >= 0
    fileline = fgets(fid);
```

```
        if fileline >= 0
            if ~isempty(findstr(fileline,'Stimulus'))
            ID=sscanf(fileline,'Stimulus, S%i, %i');
            B1 = any (ID(1)==stim);
            B2 = any (ID(1)==button);
            end

            if  B1 == 1 % start
            trialnr = trialnr +1;
            data(trialnr,1)=[trialnr];
            data(trialnr,2:3)=[ID(1),ID(2)*sample];
            response=0;
            end

            if B2 == 1 && response == 0 % response button
            data(trialnr,4:5)=[ID(1),ID(2)*sample];
            response=1;
            end



          B1 = 0;
          B2 = 0;
          end
end

processed(:,1)= data(:,1); % trialnumber
processed(:,2)= data(:,2); % stimcode
processed(:,3)= (data(:,5) - data(:,3)); % measured RT
processed(:,4)= data(:,4); % response
s=size(processed,1);
```

```
%
stimcat=1; % correct conclusion 2 premises 1st half
i=find((processed(:,2)==200)); %
j=find(((processed(:,2)==200)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==200)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=2; % incorrect conclusion 2 premises 1st half
i=find((processed(:,2)==210)); %
j=find(((processed(:,2)==210)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==210)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=3; % correct conclusion 2 premises 2nd half
i=find((processed(:,2)==201)); %
j=find(((processed(:,2)==201)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==201)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=4; % incorrect conclusion 2 premises 2nd half
i=find((processed(:,2)==211)); %
j=find(((processed(:,2)==211)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==211)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=5; % correct conclusion 3 premises 1st half
i=find((processed(:,2)==220)); %
j=find(((processed(:,2)==220)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==220)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=6; % incorrect conclusion 3 premises 1st half
i=find((processed(:,2)==230)); %
j=find(((processed(:,2)==230)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==230)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=7; % correct conclusion 3 premises 2nd half
i=find((processed(:,2)==221)); %
j=find(((processed(:,2)==221)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==221)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=8; % incorrect conclusion 3 premises 2nd half
i=find((processed(:,2)==231)); %
j=find(((processed(:,2)==231)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==231)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=9; % correct conclusion 4 premises 1st half
i=find((processed(:,2)==240)); %
j=find(((processed(:,2)==240)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==240)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=10; % incorrect conclusion 4 premises 1st half
i=find((processed(:,2)==250)); %
j=find(((processed(:,2)==250)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==250)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=11; % correct conclusion 4 premises 2nd half
i=find((processed(:,2)==241)); %
j=find(((processed(:,2)==241)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==241)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=12; % incorrect conclusion 4 premises 2nd half
i=find((processed(:,2)==251)); %
j=find(((processed(:,2)==251)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==251)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials




fname
end




OUT = targetRT
filename = ['NVS1_RT_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetPC
filename = ['NVS1_PC_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetAC
filename = ['NVS1_AC_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetAT
filename = ['NVS1_AT_v2.txt'];
dlmwrite(filename,OUT,';')
```

Experiment 2

```
DataPath='C:\Users\Tobia\Documents\Psychology Master\Thesis\BrainVision
Analyzer\Nonverbal Syllogisms\Experiment 2\Experiment 2 Export\Raw Files';
```

```
npn=input('How many data files do you want to process? ');
vpn = 1;
for vpn = 1:npn
[fname,pname] = uigetfile([DataPath,'.raw']);  % asks for the filename to analyze
fid = fopen([pname fname],'r');
sample = 1; %duration of one sample
premature = 100; %the criterion in ms for too fast responses
button = [1 2]; % 1= left (correct), 2= right (incorrect)
fileline = 0;
trialnr = 0;
B1 = 0;
B2 = 0;
ID=[];
stim = [10 11 20 21 30 31 40 41 50 51 60 61 70 71 80 81 90 91 14 15 24 25 34 35 44 45 54 55 64
65 74 75 84 85 94 95];
%   Difficulty, Half, Type, correct code, incorrect code
%   ---------------------------------------------------
%   Easy, First Half, Direct, 10, 11
%   Easy, First Half, Indirect, 20, 21
%   Easy, First Half, Simple, 30, 31
%   Medium, First Half, Direct, 40, 41
%   Medium, First Half, Indirect, 50, 51
%   Medium, First Half, Simple, 60, 61
%   Hard, First Half, Direct, 70, 71
%   Hard, First Half, Indirect, 80, 81
%   Hard, First Half, Simple, 90, 91
%   ---------------------------------------------------
%   Easy, First Half, Direct, 14, 15
%   Easy, First Half, Indirect, 24, 25
%   Easy, First Half, Simple, 34, 35
```

```
%   Medium, First Half, Direct, 44, 45
%   Medium, First Half, Indirect, 54, 55
%   Medium, First Half, Simple, 64, 65
%   Hard, First Half, Direct, 74, 75
%   Hard, First Half, Indirect, 84, 85
%   Hard, First Half, Simple, 94, 95


response = 1;
data=[];
processed=[];
while fileline >= 0
    fileline = fgets(fid);
        if fileline >= 0
            if ~isempty(findstr(fileline,'Stimulus'))
            ID=sscanf(fileline,'Stimulus, S%i, %i');
            B1 = any (ID(1)==stim);
            B2 = any (ID(1)==button);
            end

            if  B1 == 1 % start
            trialnr = trialnr +1;
            data(trialnr,1)=[trialnr];
            data(trialnr,2:3)=[ID(1),ID(2)*sample];
            response=0;
            end

            if B2 == 1 && response == 0 % response button
            data(trialnr,4:5)=[ID(1),ID(2)*sample];
            response=1;
```

```
            end

        B1 = 0;
        B2 = 0;
        end
end

processed(:,1)= data(:,1); % trialnumber
processed(:,2)= data(:,2); % stimcode
processed(:,3)= (data(:,5) - data(:,3)); % measured RT
processed(:,4)= data(:,4); % response
s=size(processed,1);


%   COLOUMS
%   ----------------------------------------------------------------------
%   Easy, First Half
stimcat=1; %  Direct, 10, CORRECT
i=find((processed(:,2)==10)); %
j=find(((processed(:,2)==10)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==10)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=2; % Direct, 11, INCORRECT
i=find((processed(:,2)==11)); %
j=find(((processed(:,2)==11)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==11)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=3; % Indirect, 20, CORRECT
i=find((processed(:,2)==20)); %
j=find(((processed(:,2)==20)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==20)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=4; % Indirect, 21, INCORRECT
i=find((processed(:,2)==21)); %
j=find(((processed(:,2)==21)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==21)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=5; % Simple, 30, CORRECT
i=find((processed(:,2)==30)); %
j=find(((processed(:,2)==30)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==30)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
```

```
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=6; %  Simple, 31, INCORRECT
i=find((processed(:,2)==31)); %
j=find(((processed(:,2)==31)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==31)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   -------------------------------------------------------------------
%   Medium, First Half
stimcat=7; %  Direct, 40, CORRECT
i=find((processed(:,2)==40)); %
j=find(((processed(:,2)==40)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==40)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
```

```
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials


stimcat=8; % Direct, 41, INCORRECT
i=find((processed(:,2)==41)); %
j=find(((processed(:,2)==41)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==41)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials


stimcat=9; % Indirect, 50, CORRECT
i=find((processed(:,2)==50)); %
j=find(((processed(:,2)==50)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==50)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
```

```
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=10; % Indirect, 51, INCORRECT
i=find((processed(:,2)==51)); %
j=find(((processed(:,2)==51)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==51)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=11; % Simple, 60, CORRECT
i=find((processed(:,2)==60)); %
j=find(((processed(:,2)==60)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==60)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
```

```
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=12; %  Simple, 61, INCORRECT
i=find((processed(:,2)==61)); %
j=find(((processed(:,2)==61)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==61)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   ---------------------------------------------------------------------
%   Hard, First Half
stimcat=13; %  Direct, 70, CORRECT
i=find((processed(:,2)==70)); %
j=find(((processed(:,2)==70)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==70)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
```

```
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=14; % Direct, 71, INCORRECT
i=find((processed(:,2)==71)); %
j=find(((processed(:,2)==71)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==71)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=15; % Indirect, 80, CORRECT
i=find((processed(:,2)==80)); %
j=find(((processed(:,2)==80)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==80)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
```

```
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=16; % Indirect, 81, INCORRECT
i=find((processed(:,2)==81)); %
j=find(((processed(:,2)==81)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==81)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=17; % Simple, 90, CORRECT
i=find((processed(:,2)==90)); %
j=find(((processed(:,2)==90)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==90)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
```

```
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=18; %  Simple, 91, INCORRECT
i=find((processed(:,2)==91)); %
j=find(((processed(:,2)==91)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==91)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   ---------------------------------------------------------------------
%   Easy, Second Half
stimcat=19; %  Direct, 14, CORRECT
i=find((processed(:,2)==14)); %
j=find(((processed(:,2)==14)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==14)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
```

```
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=20; % Direct, 15, INCORRECT
i=find((processed(:,2)==15)); %
j=find(((processed(:,2)==15)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==15)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=21; % Indirect, 24, CORRECT
i=find((processed(:,2)==24)); %
j=find(((processed(:,2)==24)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==24)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
```

```
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=22; % Indirect, 25, INCORRECT
i=find((processed(:,2)==25)); %
j=find(((processed(:,2)==25)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==25)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=23; % Simple, 34, CORRECT
i=find((processed(:,2)==34)); %
j=find(((processed(:,2)==34)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==34)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
```

```
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=24; %  Simple, 35, INCORRECT
i=find((processed(:,2)==35)); %
j=find(((processed(:,2)==35)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==35)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   ---------------------------------------------------------------------
%   Medium, Second Half
stimcat=25; %  Direct, 44, CORRECT
i=find((processed(:,2)==44)); %
j=find(((processed(:,2)==44)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==44)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
```

```
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=26; % Direct, 45, INCORRECT
i=find((processed(:,2)==45)); %
j=find(((processed(:,2)==45)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==45)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=27; % Indirect, 54, CORRECT
i=find((processed(:,2)==54)); %
j=find(((processed(:,2)==54)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==54)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
```

```
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=28; % Indirect, 55, INCORRECT
i=find((processed(:,2)==55)); %
j=find(((processed(:,2)==55)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==55)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=29; % Simple, 64, CORRECT
i=find((processed(:,2)==64)); %
j=find(((processed(:,2)==64)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==64)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
nr2 = length(k); % total of MISS trials
```

```
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=30; %  Simple, 65, INCORRECT
i=find((processed(:,2)==65)); %
j=find(((processed(:,2)==65)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==65)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   ---------------------------------------------------------------------
%   Hard, Second Half
stimcat=31; %  Direct, 74, CORRECT
i=find((processed(:,2)==74)); %
j=find(((processed(:,2)==74)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==74)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
```

```
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=32; % Direct, 75, INCORRECT
i=find((processed(:,2)==75)); %
j=find(((processed(:,2)==75)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==75)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=33; % Indirect, 84, CORRECT
i=find((processed(:,2)==84)); %
j=find(((processed(:,2)==84)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==84)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
```

```
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=34; % Indirect, 85, INCORRECT
i=find((processed(:,2)==85)); %
j=find(((processed(:,2)==85)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==85)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=35; % Simple, 94, CORRECT
i=find((processed(:,2)==94)); %
j=find(((processed(:,2)==94)) & (processed(:,4)==1)); % HIT
k=find(((processed(:,2)==94)) & (processed(:,4)==2)); % MISS
nr1 = length(j); % total of HIT trials
```

```
nr2 = length(k); % total of MISS trials
RT = mean(processed(j,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion correct
AC = nr1; % Ammount Critical (Number of Hits)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials

stimcat=36; %  Simple, 95, INCORRECT
i=find((processed(:,2)==95)); %
j=find(((processed(:,2)==95)) & (processed(:,4)==1)); % FA
k=find(((processed(:,2)==95)) & (processed(:,4)==2)); % CR
nr1 = length(j); % total of FA trials
nr2 = length(k); % total of CR trials
RT = mean(processed(k,3)); % mean RT
PC = 100*(nr1)/(nr1+nr2); % Proportion incorrect
AC = nr1; % Ammount Critical (Number of False Alarms)
AT = nr1+nr2; % Total amount of trials
targetRT(vpn,stimcat)=[RT]; % RT
targetPC(vpn,stimcat)=[PC]; % HitRate
targetAC(vpn,stimcat)=[AC]; % AmmountCritical
targetAT(vpn,stimcat)=[AT]; % Total amount of trials
%   ---------------------------------------------------------------------

fname
end
```

```
OUT = targetRT
filename = ['NVS2_RT_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetPC
filename = ['NVS2_PC_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetAC
filename = ['NVS2_AC_v2.txt'];
dlmwrite(filename,OUT,';')

OUT = targetAT
filename = ['NVS2_AT_v2.txt'];
dlmwrite(filename,OUT,';')
```

Appendix G: R code

````
```{r}
library(summarytools)
library(readxl)
library(tidyverse)
library(openxlsx)
library(gridExtra)
library(rstanarm)
library(devtools) ## only needed for installing from Github
library(knitr)
library(sjPlot)
library(sjstats)
library(sjmisc)
library(sjlabelled)
library(lme4)
library(lmerTest)
library(emmeans)
library(dplyr)
library(ggpubr)
library(effectsize)
library(MuMIn)
library(viridis)
```

```{r}
options(scipen = 999)
```

### READ IN DATA
````

```
```{r}
# Demographics

Demo_Full_NVS1 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Qualtrics/Edited/Experiment
1/NVS1_Demo_v3.xlsx")
Demo_Full_NVS2 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Qualtrics/Edited/Experiment
2/NVS2_Demo_v1.xlsx")

# Behvarioual Data

BA_Full_NVS1 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Behavioural Analysis/NVS1_BA_v5.xlsx")
BA_Full_NVS2 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Behavioural Analysis/NVS2_BA_v9.xlsx")


# Statistical Data

SA_NVS1 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Statistical analysis/SA1_Long.xlsx")
SA_NVS2 <-
  read_excel("~/Psychology Master/Thesis/Analysis/Statistical analysis/SA2_Long.xlsx")


# SEGMENTING RELEVANT DATA

##  Demographics
```
```

```
Demo1 <-
  Demo_Full_NVS1 %>%

select(Participant,Mean_d_prime,RAPM_score,Handedness,Colorblind_score,EducationLevel,N
ationality,Age,Gender)

Demo2 <-
  Demo_Full_NVS2 %>%

select(Participant,Mean_d_prime,RAPM_score,Handedness,Colorblind_score,EducationLevel,N
ationality,Age,Gender)

## Behavioural Data

BA1 <-
  BA_Full_NVS1 %>%
  select(Participant,Difficulty,Half,d_prime, RT_MeanCorrect)

BA1$Half <- factor(BA1$Half,
                    levels = c(1,2),
                    labels = c("First","Second"))

BA1$Difficulty <- factor(BA1$Difficulty,
                    levels = c(1,2,3),
                    labels = c("Easy","Medium","Hard"))

BA2 <-
  BA_Full_NVS2 %>%
  select(Participant,Difficulty,Half,d_prime, RT_MeanCorrect)
```

```
BA2$Half <- factor(BA2$Half,
                   levels = c(1,2),
                   labels = c("First","Second"))

BA2$Difficulty <- factor(BA2$Difficulty,
                   levels = c(1,2,3),
                   labels = c("Easy","Medium","Hard"))

##  Power

SA1 <-
  SA_NVS1

SA1$Difficulty <- factor(SA1$Difficulty,
                   levels = c(1,2,3),
                   labels = c("Easy","Medium","Hard"))

SA1$Window <- factor(SA1$Window,
                   levels = c(1,2,3,4,5,6,7,8,9,10),
                   labels =
c("1000","1200","1400","1600","1800","2000","2200","2400","2600","2800"))

SA1$Electrode <- factor(SA1$Electrode,
                   levels = c(1,2,3),
                   labels = c("Fz","F1","F2"))

SA2 <-
  SA_NVS2

SA2$Difficulty <- factor(SA2$Difficulty,
```

~~~
                      levels = c(1,2,3),
                      labels = c("Easy","Medium","Hard"))

SA2$Window <- factor(SA2$Window,
                      levels = c(1,2,3,4,5,6,7,8,9,10),
                      labels =
c("1000","1200","1400","1600","1800","2000","2200","2400","2600","2800"))

SA2$Electrode <- factor(SA2$Electrode,
                      levels = c(1,2,3),
                      labels = c("Fz","F1","F2"))

```

# DESCRIPTIVES
##  Demographics

```{r}
Demo1 %>%
  summarize(N_Participants = n(),
          min_Age = min(Age, na.rm = T),
          max_Age = max(Age, na.rm = T),
          mean_Age = mean(Age, na.rm = T),
          sd_Age = sd(Age, na.rm = T),
          min_RAPM = min(RAPM_score, na.rm = T),
          max_RAPM = max(RAPM_score, na.rm = T),
          mean_RAPM = mean(RAPM_score, na.rm = T),
          sd_RAPM = sd(RAPM_score, na.rm = T))
```
~~~

````
```{r}
Demo2 %>%
  summarize(N_Participants = n(),
            min_Age = min(Age, na.rm = T),
            max_Age = max(Age, na.rm = T),
            mean_Age = mean(Age, na.rm = T),
            sd_Age = sd(Age, na.rm = T),
            min_RAPM = min(RAPM_score, na.rm = T),
            max_RAPM = max(RAPM_score, na.rm = T),
            mean_RAPM = mean(RAPM_score, na.rm = T),
            sd_RAPM = sd(RAPM_score, na.rm = T))
```

```{r}
freq(Demo1$Gender,
     report.nas = FALSE, # remove NA information
     totals = FALSE, # remove totals
     cumul = FALSE, # remove cumuls
)
```

```{r}
freq(Demo2$Gender,
     report.nas = FALSE, # remove NA information
     totals = FALSE, # remove totals
     cumul = FALSE, # remove cumuls
)
```

```{r}
````
````

freq(Demo1$Nationality,
    report.nas = FALSE, # remove NA information
    totals = FALSE, # remove totals
    cumul = FALSE, # remove cumuls
)
```

```{r}
freq(Demo2$Nationality,
    report.nas = FALSE, # remove NA information
    totals = FALSE, # remove totals
    cumul = FALSE, # remove cumuls
)
```

```{r}
freq(Demo1$EducationLevel,
    report.nas = FALSE, # remove NA information
    totals = FALSE, # remove totals
    cumul = FALSE, # remove cumuls
)
```

```{r}
freq(Demo2$EducationLevel,
    report.nas = FALSE, # remove NA information
    totals = FALSE, # remove totals
    cumul = FALSE, # remove cumuls
)
```
```

````
```{r}
freq(Demo1$Handedness,
     report.nas = FALSE, # remove NA information
     totals = FALSE, # remove totals
     cumul = FALSE, # remove cumuls
)
```

```{r}
freq(Demo2$Handedness,
     report.nas = FALSE, # remove NA information
     totals = FALSE, # remove totals
     cumul = FALSE, # remove cumuls
)
```

d'

```{r}
BA1 %>%
  group_by(Half,Difficulty) %>%
  summarize(N_response = n(),
            mean_response_HR = mean(d_prime, na.rm = T),
            sd_response_HR = sd(d_prime, na.rm = T))
```

```{r}
BA2 %>%
  group_by(Half,Difficulty) %>%
````
````

````
  summarize(N_response = n(),
            mean_response_dP = mean(d_prime, na.rm = T),
            sd_response_dP = sd(d_prime, na.rm = T))
```

##  Reaction times

```{r}
BA1 %>%
  group_by(Half,Difficulty) %>%
  summarize(N_response = n(),
            mean_response_CorrectRT = mean(RT_MeanCorrect, na.rm = T),
            sd_response_CorrectRT = sd(RT_MeanCorrect, na.rm = T))
```

```{r}
BA2 %>%
  group_by(Half,Difficulty) %>%
  summarize(N_response = n(),
            mean_response_CorrectRT = mean(RT_MeanCorrect, na.rm = T),
            sd_response_CorrectRT = sd(RT_MeanCorrect, na.rm = T))
```

Statisical data

NVS1

####Lower theta

```{r}
````

SA1 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_LT = mean(Power_LT, na.rm = T),
            sd_Power_LT = sd(Power_LT, na.rm = T))
```

####Middle theta

```{r}
SA1 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_MT = mean(Power_MT, na.rm = T),
            sd_Power_MT = sd(Power_MT, na.rm = T))
```

####Upper theta

```{r}
SA1 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_UT = mean(Power_UT, na.rm = T),
            sd_Power_UT = sd(Power_UT, na.rm = T))
```

NVS2

####Lower theta
```

```{r}
SA2 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_LT = mean(Power_LT, na.rm = T),
            sd_Power_LT = sd(Power_LT, na.rm = T))
```

####Middle theta

```{r}
SA2 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_MT = mean(Power_MT, na.rm = T),
            sd_Power_MT = sd(Power_MT, na.rm = T))
```

####Upper theta

```{r}
SA2 %>%
  group_by(Difficulty) %>%
  summarize(N_response = n(),
            mean_Power_UT = mean(Power_UT, na.rm = T),
            sd_Power_UT = sd(Power_UT, na.rm = T))
```

Statistical Data

NVS1

Lower theta

```{r}
SA1 %>%
  group_by(Electrode, Difficulty) %>%
  summarize(N_response = n(),
            mean_response_Power_LT = mean(Power_LT, na.rm = T),
            sd_response_Power_LT = sd(Power_LT, na.rm = T))
```

Middle theta

```{r}
SA1 %>%
  group_by(Electrode, Difficulty) %>%
  summarize(N_response = n(),
            mean_response_Power_MT = mean(Power_MT, na.rm = T),
            sd_response_Power_MT = sd(Power_MT, na.rm = T))
```

Upper theta

```{r}
  SA1 %>%
    group_by(Electrode, Difficulty) %>%
    summarize(N_response = n(),
```

~~~~
            mean_response_Power_UT = mean(Power_UT, na.rm = T),
            sd_response_Power_UT = sd(Power_UT, na.rm = T))
```

#   Behavioural analysis

##  NVS1

### Correlation between RAPM and mean d'

```{r}
shapiro.test(Demo1$RAPM_score)
```

```{r}
shapiro.test(Demo1$Mean_d_prime)
```

```{r}
cor.test(Demo1$RAPM_score, Demo1$Mean_d_prime, method = "pearson")
```

```{r}
cor.test(Demo1$RAPM_score, Demo1$Mean_d_prime, method = "spearman")
```

```{r}
Demo1 %>%
  ggplot(data, mapping=aes(x=RAPM_score, y=Mean_d_prime, na.rm = T)) +
  geom_point() +
~~~~

```
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "RAPM score", y = "Mean d'")
```

d'

```{r}
M_BA1_dP<-lmer(d_prime~Difficulty*Half+(1|Participant),data=BA1)
anova(M_BA1_dP)
eta_squared(M_BA1_dP, partial = TRUE)
```

```{r}
emmeans(M_BA1_dP, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_BA1_dP, list(pairwise~Half), adjust= "tukey")
emmeans(M_BA1_dP, list(pairwise~Half|Difficulty), adjust= "tukey")
```

```{r}
qqnorm(resid(M_BA1_dP))
```

```{r}
BA1_dP <-
  BA1 %>%
    group_by(Half, Difficulty) %>%
    summarize(N_response = n(),
```

```
        mean_dP = mean(d_prime, na.rm = T),
        sd_dP = sd(d_prime, na.rm = T))

BA1_dP %>%
  ggplot(aes(x=Difficulty, y=mean_dP, fill=Half)) +
    geom_bar(stat = "identity",
        position = "dodge") +
    theme_bw() +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Difficulty", y = "Mean d'")
```

Reaction Time

```{r}
M_BA1_RT<-lmer(RT_MeanCorrect~Difficulty*Half+(1|Participant),data=BA1)
anova(M_BA1_RT)
eta_squared(M_BA1_RT, partial = TRUE)
```

```{r}
emmeans(M_BA1_RT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_BA1_RT, list(pairwise~Half), adjust= "tukey")
```

```{r}
qqnorm(resid(M_BA1_RT))
```

````
```

```{r}
BA1_RT <-
  BA1 %>%
    group_by(Half, Difficulty) %>%
    summarize(N_response = n(),
              mean_RT = mean(RT_MeanCorrect, na.rm = T),
              sd_RT = sd(RT_MeanCorrect, na.rm = T))

BA1_RT %>%
  ggplot(aes(x=Difficulty, y=mean_RT, fill=Half)) +
    geom_bar(stat = "identity",
           position = "dodge") +
    theme_bw() +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Difficulty", y = "Mean Reaction Time")
```

## NVS2

```{r}
shapiro.test(Demo2$RAPM_score)
```

```{r}
shapiro.test(Demo2$Mean_d_prime)
```
````
````

````
```{r}
cor.test(Demo2$RAPM_score, Demo2$Mean_d_prime, method = "pearson")
```

```{r}
cor.test(Demo2$RAPM_score, Demo2$Mean_d_prime, method = "spearman")
```

```{r}
Demo2 %>%
  ggplot(data, mapping=aes(x=RAPM_score, y=Mean_d_prime, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "RAPM score", y = "Mean d'")
```

d'

```{r}
M_BA2_dP<-lmer(d_prime~Difficulty*Half+(1|Participant),data=BA2)
anova(M_BA2_dP)
eta_squared(M_BA2_dP, partial = TRUE)
```

```{r}
emmeans(M_BA2_dP, list(pairwise~Difficulty), adjust= "tukey")
```
````

```{r}
BA2_dP <-
  BA2 %>%
    group_by(Half, Difficulty) %>%
    summarize(N_response = n(),
              mean_dP = mean(d_prime, na.rm = T),
              sd_dP = sd(d_prime, na.rm = T))

BA2_dP %>%
  ggplot(aes(x=Difficulty, y=mean_dP, fill=Half)) +
    geom_bar(stat = "identity",
           position = "dodge") +
    theme_bw() +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Difficulty", y = "Mean d'")
```

### Reaction Time

```{r}
M_BA2_RT<-lmer(RT_MeanCorrect~Difficulty*Half+(1|Participant),data=BA2)
anova(M_BA2_RT)
eta_squared(M_BA2_RT, partial = TRUE)
```

```{r}
emmeans(M_BA2_RT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_BA2_RT, list(pairwise~Half), adjust= "tukey")
```

````
```


```{r}
BA2_RT <-
  BA2 %>%
    group_by(Half, Difficulty) %>%
    summarize(N_response = n(),
              mean_RT = mean(RT_MeanCorrect, na.rm = T),
              sd_RT = sd(RT_MeanCorrect, na.rm = T))

BA2_RT %>%
  ggplot(aes(x=Difficulty, y=mean_RT, fill=Half)) +
    geom_bar(stat = "identity",
           position = "dodge") +
    theme_bw() +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Difficulty", y = "Mean Reaction Time")
```
````

Statistical analysis

Adjusted p-value = $\sqrt{}(0.05/([\text{nr. of time windows-1}] * [\text{nr. of electrodes}] * [\text{nr. of bands}] * [\text{nr. of tests}])$

$p(crit) < 0.009 = \sqrt{}(0.05/([10-1] * [3] * [3] * [7])$

$p(\text{Post hoc: Difficulty, condition}) < 0.014 = \sqrt{}(0.05/([10-1] * [3] * [3] * [3]$

$p(\text{Post hoc: Window}) < 0.0006 = \sqrt{}(0.05/([10-1] * [3] * [3] * [45]$
````

## NVS1

### Correlation between d' and theta acitivty

```{r}
BSA1 <-
  SA1 %>%
    group_by(Participant) %>%
      summarize(N_response = n(),
                mean_LT = mean(Power_LT, na.rm = T),
                sd_LT = sd(Power_MT, na.rm = T),
                mean_MT = mean(Power_MT, na.rm = T),
                sd_MT = sd(Power_MT, na.rm = T),
                mean_UT = mean(Power_UT, na.rm = T),
                sd_UT = sd(Power_UT, na.rm = T),
                mean_T = mean(Power_T, na.rm = T),
                sd_T = sd(Power_T, na.rm = T))

BSA1 <-
  merge(x=BSA1,y=Demo1,by="Participant",all.y=TRUE)
```

```{r}
shapiro.test(BSA1$mean_LT)
```

```{r}
shapiro.test(BSA1$mean_MT)
```

````
```{r}
shapiro.test(BSA1$mean_UT)
```

```{r}
shapiro.test(BSA1$mean_T)
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_LT, method = "pearson")
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_LT, method = "spearman")
```

```{r}
BSA1 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_LT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Lower Theta ERS/ERD")
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_MT, method = "pearson")
````
````

````
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_MT, method = "spearman")
```

```{r}
BSA1 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_MT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Middle Theta ERS/ERD")
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_UT, method = "pearson")
```

```{r}
cor.test(Demo1$Mean_d_prime, BSA1$mean_UT, method = "spearman")
```

```{r}
BSA1 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_UT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
````

````
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Upper Theta ERS/ERD")
```

### Lower theta

```{r}
M_SA1_LT <- lmer(Power_LT ~ Difficulty*Window*Electrode + (1|Participant), data=SA1)
anova(M_SA1_LT)
eta_squared(M_SA1_LT, partial = TRUE)
```

```{r}
emmeans(M_SA1_LT, list(pairwise~Window), adjust= "tukey")
```

```{r}
SA1_LT <-
  SA1 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_LT = mean(Power_LT, na.rm = T),
              sd_response_Power_LT = sd(Power_LT, na.rm = T))

SA1_LT %>%
  ggplot(aes(x=Time, y=mean_response_Power_LT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
````

````
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```

### Middle theta

```{r}
M_SA1_MT <- lmer(Power_MT ~ Difficulty*Window*Electrode + (1|Participant), data=SA1)
anova(M_SA1_MT)
eta_squared(M_SA1_MT, partial = TRUE)
```

```{r}
emmeans(M_SA1_MT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_SA1_MT, list(pairwise~Window), adjust= "tukey")
emmeans(M_SA1_MT, list(pairwise~Electrode), adjust= "tukey")
```

```{r}
SA1_MT <-
  SA1 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_MT = mean(Power_MT, na.rm = T),
              sd_response_Power_MT = sd(Power_MT, na.rm = T))

SA1_MT %>%
````

```
  ggplot(aes(x=Time, y=mean_response_Power_MT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```

Upper theta

```{r}
M_SA1_UT <- lmer(Power_UT ~ Difficulty*Window*Electrode + (1|Participant), data=SA1)
anova(M_SA1_UT)
eta_squared(M_SA1_UT, partial = TRUE)
```

```{r}
emmeans(M_SA1_UT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_SA1_UT, list(pairwise~Window), adjust= "tukey")
emmeans(M_SA1_UT, list(pairwise~Electrode), adjust= "tukey")
```

```{r}
SA1_UT <-
  SA1 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_UT = mean(Power_UT, na.rm = T),
```

~~~
          sd_response_Power_UT = sd(Power_UT, na.rm = T))

SA1_UT %>%
  ggplot(aes(x=Time, y=mean_response_Power_UT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```

##  NVS2

### Correlation between d' and theta acitivty

```{r}
BSA2 <-
  SA2 %>%
    group_by(Participant) %>%
      summarize(N_response = n(),
            mean_LT = mean(Power_LT, na.rm = T),
            sd_LT = sd(Power_MT, na.rm = T),
            mean_MT = mean(Power_MT, na.rm = T),
            sd_MT = sd(Power_MT, na.rm = T),
            mean_UT = mean(Power_UT, na.rm = T),
            sd_UT = sd(Power_UT, na.rm = T),
            mean_T = mean(Power_T, na.rm = T),
            sd_T = sd(Power_T, na.rm = T))
~~~

~~~~
BSA2 <-
  merge(x=BSA2,y=Demo2,by="Participant",all.y=TRUE)

```

```{r}
shapiro.test(BSA2$mean_LT)
```

```{r}
shapiro.test(BSA2$mean_MT)
```

```{r}
shapiro.test(BSA2$mean_UT)
```

```{r}
shapiro.test(BSA2$mean_T)
```

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_LT, method = "pearson")
```

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_LT, method = "spearman")
```
~~~~

~~~~
```{r}
BSA2 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_LT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Lower Theta ERS/ERD")
```

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_MT, method = "pearson")
```

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_MT, method = "spearman")
```

```{r}
BSA2 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_MT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Middle Theta ERS/ERD")
```
~~~~

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_UT, method = "pearson")
```

```{r}
cor.test(Demo2$Mean_d_prime, BSA2$mean_UT, method = "spearman")
```

```{r}
BSA2 %>%
  ggplot(data, mapping=aes(x=Mean_d_prime, y=mean_UT, na.rm = T)) +
  geom_point() +
  geom_smooth(method="lm") +
  theme_bw() +
  scale_color_viridis(discrete = TRUE, option = "viridis") +
  scale_fill_viridis(discrete = TRUE) +
  labs(x = "Mean d'", y = "Mean Upper Theta ERS/ERD")
```

Lower theta

```{r}
M_SA2_LT <- lmer(Power_LT ~ Difficulty*Window*Electrode + (1|Participant), data=SA2)
anova(M_SA2_LT)
eta_squared(M_SA2_LT, partial = TRUE)
```

```{r}
emmeans(M_SA2_LT, list(pairwise~Window), adjust= "tukey")
emmeans(M_SA2_LT, list(pairwise~Electrode), adjust= "tukey")
```

````
emmeans(M_SA2_LT, list(pairwise~Difficulty|Electrode), adjust= "tukey")
```

```{r}
SA2_LT <-
  SA2 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_LT = mean(Power_LT, na.rm = T),
              sd_response_Power_LT = sd(Power_LT, na.rm = T))

SA2_LT %>%
  ggplot(aes(x=Time, y=mean_response_Power_LT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```

### Middle theta

```{r}
M_SA2_MT <- lmer(Power_MT ~ Difficulty*Window*Electrode + (1|Participant), data=SA2)
anova(M_SA2_MT)
eta_squared(M_SA2_MT, partial = TRUE)
```
````
````

````
```{r}
emmeans(M_SA2_MT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_SA2_MT, list(pairwise~Window), adjust= "tukey")
emmeans(M_SA2_MT, list(pairwise~Electrode), adjust= "tukey")
```

```{r}
SA2_MT <-
  SA2 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_MT = mean(Power_MT, na.rm = T),
              sd_response_Power_MT = sd(Power_MT, na.rm = T))

SA2_MT %>%
  ggplot(aes(x=Time, y=mean_response_Power_MT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```

### Upper theta

```{r}
M_SA2_UT <- lmer(Power_UT ~ Difficulty*Window*Electrode + (1|Participant), data=SA2)
anova(M_SA2_UT)
````
````

```
eta_squared(M_SA2_UT, partial = TRUE)
```

```{r}
emmeans(M_SA2_UT, list(pairwise~Difficulty), adjust= "tukey")
emmeans(M_SA2_UT, list(pairwise~Window), adjust= "tukey")
emmeans(M_SA2_UT, list(pairwise~Electrode), adjust= "tukey")
```

```{r}
SA2_UT <-
  SA2 %>%
    group_by(Time, Difficulty, Electrode) %>%
    summarize(N_response = n(),
              mean_response_Power_UT = mean(Power_UT, na.rm = T),
              sd_response_Power_UT = sd(Power_UT, na.rm = T))

SA2_UT %>%
  ggplot(aes(x=Time, y=mean_response_Power_UT, col=Difficulty, group=Difficulty)) +
    geom_line() +
    geom_point() +
    theme_bw() +
    facet_grid(Electrode ~ .) +
    scale_color_viridis(discrete = TRUE, option = "viridis") +
    scale_fill_viridis(discrete = TRUE) +
    labs(x = "Time", y = "Percentage Change of Power")
```