BRAIN DYNAMICS AND BEHAVIORAL BASIS OF A HIGHER LEVEL COGNITIVE TASK: NUMBER COMPARISON

by

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This dissertation was prepared under the direction of the candidate's dissertation advisor, Dr. Robert Stackman, Center for Complex Systems and Brain Sciences, and has been approved by the members of her supervisory committee. It was submitted to the faculty of the Charles E. Schmidt College of Science and was accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

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Number perception, its neural basis and its relationship to how numerical stimuli are presented have been challenging research topics in cognitive neuroscience for many years. A primary question that has been addressed is whether the perception of the quantity of a visually presented number stimulus is dissociable from its early visual perception. The present study examined the possible influence of visual quality judgment on quantity judgments of numbers. To address this issue, volunteer adult subjects performed a mental number comparison task in which two-digit stimulus numbers (Arabic number format), among the numbers between 31 and 99 were mentally compared to a memorized reference number, 65.

Reaction times (RTs) and neurophysiological (i.e. electroencephalographic (EEG) data) responses were acquired simultaneously during performance of the two-digit number comparison task. In this particular quantity comparison task, the number stimuli were classified into three distance factors. That is, numbers were a close, medium or far distance from the reference number (i.e., 65). In order to evaluate the relationship between numerical stimulus quantity and quality, the number stimuli were embedded in varying degrees of a typical visual noise form, known as “salt and pepper noise” (e.g., the visual noise one perceives when viewing a photograph taken with a dusty camera lens). In this manner, the visual noise permitted visual quality to be manipulated across three levels: no noise, medium noise (approximately 60% degraded visual quality from no-noise), and dense noise (75% degraded visual quality from no-noise). The RTs provided the information about the overt responses; however, the temporal relationship of visual quality (starts earlier than quantity perception) and quantity were examined using event-related potentials (ERPs) extracted from continuous EEG recordings.

The analysis of the RTs revealed that the judgment of number quantity is dependent upon visual number quality. In addition, the same effect was observed over the ERP components occurring between 100 ms and 300 ms after stimulus onset time over the posterior electrodes. Principal components analysis (PCA) and independent component analysis (ICA) methods were used to further analyze the ERP data. The consistent results of the PCA and ICA were used to represent the spatial brain dynamics, as well as to obtain temporal dynamics. The overall conclusion of the present study is that ERPs, ICs and PCs along with RTs suggested a strategy of quantitative perception (i.e., number comparison) based on the qualitative attributes of the stimuli highlighting the importance of the design of the task and the methodology.

BRAIN DYNAMICS AND BEHAVIORAL BASIS OF A HIGHER LEVEL COGNITIVE TASK: NUMBER COMPARISON

TABLES x

FIGURES xi

I. INTRODUCTION 1

Mental Number Line 1

Numerical Distance 3

Quantitative Attributes of Visual Stimuli 6

The Relationship between Quality Judgment and Quantity Judgment 6

Two-Digit Number Perception 8

Effects of Sensory Quality on Number Perception 9

The Role of IPS on Number Perception 10

ERP Studies and Common ERP Components of Number Comparison 13

Debates on Number Processing 14

PCA and ICA Studies in the ERPs Literature 16

II. A NUMBER COMPARISON EXPERIMENT 18

Overview 18

Aims and Objectives of the Study 20

Hypothesis and Predictions 23

Predicted Perception Model 23

Methods..27

  Participants 27

  Number Comparison Task Procedure 27

  EEG Recording and Data Acquisition 33

  Obtaining the RTs 33

Data Analyses...33

  Behavioral Data 33

  ERP Data 34

Results..38

  Behavioral Results 38

  ERP Results 43

  First Posterior Positivity: P1 (100 ms - 130 ms) 44

  First Posterior Negativity: N1 (130 - 160 ms)...44

  Second Posterior Positivity: P2p (175 ms)..45

  Second Fronto-central Negativity: N2 (180–250ms)...................................45

  The Late Posterior Positive Component 46

PCA and ICA Results 51

Statistical Analysis of PCA/ICA 56

  Statistical Analysis of PCA Components..56

PC1 56
PC2 58
PC3 59
Statistical Analysis of ICA Components 60
IC1 60
IC2 62
IC3 63
III. DISCUSSION 67
Behavioral Results 68
Electrophysiological Results 69
Evaluation of Visual Quality 72
Evaluation of Quantity 73
Evaluation of Visual Quality and Quantity Together 74
PCA and ICA Results 74
Relationship between ERP and RT Results 75
Conclusion 77
Possible Implications of the Results 80
Limitations of the Current Study and Future Studies 81
IV. APPENDIX I DESIGNING and TESTING THE TASK PARAMETERS 83
Materials and Methods 83

Subjects 83

Tools 83

Procedure of the Pilot Behavioral Task 84

Preliminary Results and Comments 87

Results I..87

Comment I...89

Results II 90

Comment II..91

Final Task Design 91

Results and Discussion of Pilot Study 94

Behavioral Results and Discussion...94

Discussion 99

ERP Results and Discussion...100

Conclusion...103

V. APPENDIX III SUPPLEMENTARY ERPs and ICs 105

Midline Electrodes..105

Retinal Activities 109

IC Components..110

BIBLOGRAPHY 111

TABLES

Table II-1 The numbers chosen. 32

Table II-2 Summary of statistical significance of ERPs 50

Table II-3 Results of the ICA and PCA. 55

Table II-4 The summary of the PC1 and IC1 statistical analyses 64

Table II-5 Summary of the PC2 and IC2 statistical analyses 65

Table II-6 Summary of the PC3 and IC3 statistical analyses 66

Table III-1 Quality and quantity interactions 71

Table IV-1 The number stimuli. 86

Table IV-2 Behavioral results of the first pilot task. 87

Table IV-3 Error rate. 88

Table IV-4 Errors for stimuli with fixation asterisk. 90

Table IV-5 Mean omitted answers for each block. 98

FIGURES

Figure II-1 A model of the processes involved in the number comparison task..............26

Figure II-2 Representative example of the number stimulus presentation 30

Figure II-3 Example trial from the two-digit number comparison task. 31

Figure II-4 A flattened representation of the high-density EEG....................................37

Figure II-5 Averaged reaction times of EEG participants. 40

Figure II-6 The RT comparison. 41

Figure II-7 The RT comparison 42

Figure II-8 Noise modulation of P6 electrode...47

Figure II-9 Central posterior electrode (Cz). 48

Figure II-10 Hemispheric brain dynamics of PO7 (left) /PO8 (right).............................49

Figure II-11 Temporal and spatial dynamics of largest IC and PC.................................52

Figure II-12 Temporal and spatial dynamics of the second largest IC and PC 53

Figure II-13 Temporal and spatial dynamics of the third largest IC and PC...................54

Figure IV-1 A single trial representing the first reaction time task................................85

Figure IV-2 Final task design...93

Figure IV-3 Block-wise distance effect on RT (in ms). 95

Figure IV-4 Block-wise noise effect on the RT (in ms). 96

Figure IV-5 The topographical representations of temporal ERPs 101

Figure IV-6 The ERP components over the occipital and parietal lobes. 102

Figure V-1 Frontal midline electrodes...105

Figure V-2 Central midline electrodes. 106

Figure V-3 Posterior midline electrodes.. 107

Figure V-4 Supplementary posterior and occipital electrodes......................................108

Figure V-5 Eye movement activity. 109

Figure V-6 Three IC components in shorter windows centering the ERP peaks...........110

I. INTRODUCTION

Understanding the functional organization of mental processes and their related anatomical organization is a main challenge in cognitive neuroscience. The behavioral neuroscience provides useful information about participants' responses to a certain task; however, the behavioral data is not enough to understand the functional and structural mechanisms of the brain. In this context, brain imaging technologies are often used to record the relevant activity to understand the underlying mechanisms of a certain behavior.

In particular, the motivation of present study is to understand the behavioral and brain dynamics of relationship between the visual quality and the perception of numerical quantity (i.e., distance from a reference number). The current study proposed that visual quality and quantity processes are organized in a sequential order; but exhibit dependent processes. In other words, the visual quality process begins first and before it is completed, the quantity process begins. The current study addresses the question of how this interaction evolves. Therefore, revisiting previous number perception studies will provide some insight into the selection criterion of the particular study.

Mental Number Line

The first modern studies of number strategy were conducted over 100 years ago by Sir Francis Galton (1880a, 1880b). Galton asked his subjects to draw lines on a paper to depict given intervals of numbers, and subsequently reported that subjects used a mental representation of the number, which may be used by each person during daily activities. Galton (1880a, 1880b) suggested that a mental map of numbers automatically and involuntarily appears whenever a person makes judgments of quantity. Each mental number is assigned in a mental order on an imaginary line in the brain. This number line evoked a sense of quantity and spatiality.

Dehaene, Dupoux and Mehler (1990) studied the spatiality of numbers by asking their subjects to press a key to the left for numbers larger than a reference number, and to press a key to the right for smaller numbers. An interesting pattern appeared, after counterbalancing with the converse condition, on average, participants respond faster to smaller numbers with the left key and to larger numbers with the right key. Dehaene and Mehler (1992) examined the effect of response side and named the finding as the Spatial-Numerical Association of Response Codes (known by its acronym, SNARC). The SNARC effect has been interpreted as evidence that numbers are coded spatially in the brain. The coding appears to be relative: the same number will show a left-side advantage if it is smaller than the reference number in one condition and a right-side advantage if it is larger than the reference in the next condition. The effect appears when numbers are presented as Arabic digits or as written words, suggesting that the effect is mediated by abstract representations, rather than any characteristics of the visual form of the stimuli. The finding of an automatic spatial numerical association was correlated to the mental number line concept of Galton (1880a, 1880b). In this context, the number line was divided into elementary groups according to spatiality and quantity in comparison to a reference number. For example, close numbers to a reference number are represented at an adjoint location reflecting the numerical distance effect.

Numerical Distance

In their seminal paper, Moyer and Landauer (1967) suggested that the spatial distance between two numbers on the mental number line impacts subjects’ RTs. For example, the reaction time to decide whether the number 6 is larger than 5 is longer than that required to decide the relative quantity of 9. The well-known name for this phenomenon is the distance effect. In the same article, Moyer et al. (1967) suggested that the distance between two numbers is judged similarly to how the distance between two physical stimuli is judged (e.g., format of line and length of the line). Moyer et al. (1967) explored the nature of the process involved in adults' choice of a larger number by examining the time that the process requires. Stimuli consisted of two 1-digit numbers 2.5 cm. apart on a white background. Participants pressed the left or right of two switches depending on the placement of the larger number. Results showed that decision time was approximately a linear inverse function of the numerical differences between the 2 stimulus digits. It is suggested that this process is analogous to the process involved in judgments of inequality for physical continua. Many researchers agree with the finding of Moyer et al. (1967) regarding single digit numbers (McCloskey, Caramazza, and Basili, 1985; Dehaene et al., 1992; McCloskey, 1992; Campbell, 1994; Cipolotti and Butterworth, 1995; Dehaene and Cohen, 1995; Noel and Seron, 1997).

Cipolotti et al. (1995) presented a case study, a patient, identified by his initials, S.A.M., who suffered from a progressive neurological degenerative condition of unknown origin with a severe difficulty in number transcoding tasks. The transcoding tasks are developed to understand the subject’s ability to understand number perception in different formats. For example, when the numerical stimulus in Arabic format appears on the stimulus monitor (e.g., 5) the subject is asked to write the number in verbal format (e.g., five). S.A.M. could recognize and understand Arabic and written verbal numbers, but he could not transcode the numbers (e.g., Arabic format to verbal format). S. A. M.'s performance on the tasks suggested that deficits affecting the ability to produce Arabic or verbal numerals can be specific to particular task demands. Accordingly, Dehaene and Akhavein (1995) suggested that Arabic and verbal numerals appear to converge toward a common semantic representation of quantities. Subjects performed a numerical pair matching task in 2 conditions: quantity matching (i.e., same quantity, 2-TWO), or quality matching (i.e., different quality, 2-TWO). The distance effect was observed indicating that numbers were automatically converted mentally into quantities, even when the participants had been told to attend exclusively to their physical characteristics. As postulated by several models of number processing (e.g., Dehaene, 1992; McCloskey, 1992), Arabic and verbal numerals thus appear to converge toward a common semantic representation of quantities.

Accordingly, Noel et al. (1997) discussed whether different formats activate exactly the same semantic representations. Results of experiments suggested that different intermediate representations are activated, depending on the lexico-syntactic structure of the numeral to be processed such that: (1) equation verification is faster when the calculation mimics the structure of the Roman numeral proposed as a solution (e.g., VII = 5 + 2), (2) comparing the magnitude of two verbal numerals is more rapid when the two items share the same lexico-syntactic structure (e.g., twelve hundred, fourteen hundred) than when the two items do not share the same lexico-syntactic structure (e.g., twelve hundred, one thousand four hundred), (3) when calculating orally, participants tend to use the same verbal structure to express their response as the one used in the stimulus problems. Thus, an intermediate level of representation occurs between the input form and the semantic representation. Such an intermediate representation would express the semantic relationships that are captured by the sensory format through the selected lexical items and the syntactic relationships that combine them (Noel et al., 1997).

Quantitative Attributes of Visual Stimuli

Recently, Burr and Ross (2008a, 2008b) suggested that number processing is a basic visual system feature in the context of comparing two scenes in the temporal domain. They suggested that perceived numerosity is susceptible to adaptation, like primary visual properties of a scene, such as color, contrast, size, and speed. Number perception was decreased by adaptation to large numbers of dots on a visual display surrounding the stimulus and increased by adaptation to small numbers of dots, the effect depending entirely on the numerosity of the adaptor, not on contrast, size, orientation, or pixel density, and occurring with very low adaptor contrasts. An earlier paper by Durgin (1995, 2008) suggested a similar conclusion, namely, that multiple information types, such as texture density and cluster, have an effect on number quantity perception.

The Relationship between Quality Judgment and Quantity Judgment

Human information processing is very proficient in distinguishing between quantities and qualities of numbers (e.g., luminance, size) even when one of the attributes is irrelevant to the attended stimulus. This is referred to as automatic processing, which is controlled by some unattended attributes such as the size of the number stimulus, the contrast between number stimulus and the background; all of this referring to the visual quality of number. In other words, the irrelevant unattended attributes change the process of attended relevant stimulus (Tzelgov, 1997; Tzelgov, Yehene, Kotler and Alon, 2000). The size congruity effect is one of the common examples of the influence of the physical size of a numerical stimulus on the perceived quantity of that number. As an example of the size congruity effect, participants were asked to compare numbers in two scenarios:

one with the larger number presented in larger format and smaller in smaller format (i.e., font size; e.g., larger font 7 versus smaller font 5) and another with the larger number in smaller format and smaller number in larger format (e.g., smaller font 7 versus larger font 5). The RTs are, in the first scenario, expected to be faster than the second one because of the congruity between visual size and quantity of the numerical stimulus. Therefore, the size and quantity that numbers convey are processed even when format of number (i.e., font size) is completely irrelevant to the task at hand, or when they clearly interfere with processing the attended dimension.

Henik et al. (1982) examined the influence of an irrelevant variable in a comparative judgment task in two experiments. Thirty-six college students were asked to compare two one-digit number stimuli presented either as incongruent physical size and quantity, the larger physical format for smaller number quantity or smaller physical format for larger number quantity, or congruent physical size and quantity, the larger physical format for larger number quantity or smaller physical format for smaller number quantity. RTs were facilitated when the irrelevant dimension was congruent with the relevant dimension and were inhibited when two dimensions were incongruent (size congruity effect). Although judgments based on physical size were faster, their speed was affected by the numerical distance between the members of the digit pair, indicating that numerical distance is automatically computed even when it is irrelevant to the comparative judgment being required by the task.

Two-Digit Number Perception

Several studies used similar strategies to understand two-digit number perception. In processing two-digit numbers, the underlying mechanisms seem to change. Two-digit numbers may not be processed as a whole because both numeric components (the ones and the tens places) are taken into account in a comparative judgment. Hinrichs, Yurko and Hu (1981) studied two-digit numbers between 11 and 99 in two comparison tasks with memorized reference numbers, either 50 or 55. Results of two experiments with 137 undergraduates suggested that the ones-place digit significantly affected RTs even when the tens-place digit was logically sufficient to select the correct response. The RT results exhibited a logarithmic function of the absolute difference between the two numbers. RTs decreased as numerical distance from the reference number increased.

Dehaene et al. (1990) investigated the numbers between 31 and 99 in a similar number comparison task with a memorized reference number of 65. Thirty-five adult volunteers classified the number stimulus as being smaller or larger than the reference number. The results suggested that the RTs became increasingly larger as the number stimulus got closer to 65. Thus, deciding that 72 is larger than 65 may take longer than deciding that 76 is larger than 65. In other words, when making a judgment of numerical quantity of a two-digit number (e.g., 72), it is not sufficient to process only the tens-place digit (e.g., 7). Nuerk, Weger and Willmes (2001) tested the ones-place digit and tens-place digit compatibility in a paired comparison task such that the participants were asked to compare two numbers simultaneously presented on the screen. In one scenario, the ones-place digit comparison and ones-place digit comparison would lead to the same response (e.g. 52 and 67) and in another, would not lead to the same response (e.g. 47 and 62). Nuerk et al. (2001) suggested that the logarithmic distance effect is a very strong indicator of number perception but it does not generalize to all numbers. The study showed a competitive effect between ones-place digit and tens-place digit. Therefore, the RTs would change with not only the distance from a reference number but also the place of the digits.

Effects of Sensory Quality on Number Perception

Accordingly, several studies examined similar effects, studied with single digit numbers, to understand the relationship between the sensory model (e.g., size of the number, visual quality of the number stimuli) and the two-digit number perception. The size congruity effect is one of the well-characterized studies in this context. The size congruity effect refers to the fact that comparisons of the sizes of the physical formats in which numerals appear are affected by the numerical magnitudes of the respective numerals. Foltz et al. (1984) studied size congruity effect with both Arabic numbers (e.g., 32) and verbal numbers (e.g., thirty-two); for Arabic numbers the interference caused by size incongruity was greater than the facilitation caused by size congruity, whereas for verbal numbers, the facilitation was greater than the interference. This finding suggested that visual quality of the numbers affects the mental quantity judgment. Accordingly, Ganor-Stern et al. (2007) studied the size congruency effect of two-digit numbers using a similar compatibility approach by Nuerk et al. (2001). The size congruency effect was affected by the compatibility between ones-place and tens-place digits. Thus the physical representation of the numerals influences the quantitative judgment of the numerals.

The Role of IPS on Number Perception

One of the biggest challenges of cognitive neuroscience is to isolate the specific brain regions and circuits involved in a particular cognitive task. Studies of brain damaged patients with brain tumors using invasive and non-invasive brain imaging studies have provided evidence that the intraparietal sulcus (IPS) is engaged during number perception task. The IPS is located on the lateral surface of the parietal lobe, and consists of an oblique and a horizontal portion. Behavioral studies suggest that the IPS is associated with impairments of basic numerical magnitude processing. Furthermore, there is a pattern of structural and functional alternations in the IPS and in the prefrontal cortex (PFC) in dyscalculia (Ansari, and Karmiloff-Smith, 2002).

Pinel et al. (2001) used event-related fMRI and high-density ERPs to understand the cerebral activities that are influenced by numerical format (i.e., verbal number vs. Arabic number). The bilateral extrastriate cortices and a left precentral region were more activated during verbal number than during Arabic number stimulation, while the right fusiform gyrus and a set of bilateral inferoparietal and frontal regions were more activated during Arabic number than during verbal number stimulation. These results support the assumption of a central semantic representation of numerical quantity that relies on a common parietal network shared across notation styles.

Moreover, using fMRI Fias, et al. (2003) hypothesized that those regions in and around the IPS were also involved in the quantitative processing of non-symbolic stimuli. The study consisted of three comparison tasks, angles, lines, and two-digit number pairs. One of the pairs (i.e., number, lines or angles) was presented on the left and the other on the right-hand sides of the fixation point. Eighteen participants pressed the key on the side representing the largest numeric quantity. They isolated a site in left IPS that was specifically active when two stimuli had to be compared along a quantitative dimension for all of the three comparison tasks. Hence, the left IPS can be considered a neural correlate of number quantity, independent of sensory quality. However, the interaction between task and type of stimulus identified a region anterior to the IPS, more specifically its horizontal segment, not specific for quantitative processing, but reflecting general processes engaged by number processing. The latter finding by Fias et al. (2003) addressed a possible interaction between early visual processing and number perception on a region anterior of IPS. Overall, it is commonly accepted that IPS is involved in number perception. Moreover, the IPS is also thought to play a role in other functions, including processing symbolic numerical information, termed visuospatial working memory.

Cohen-Kadosh and Henik (2006) studied the mutual interference between luminance and numerical values involved in numerical magnitude judgments using fMRI. Rather than manipulating the physical size of compared numbers, which is the traditional approach in size congruity studies (i.e. comparing larger font 35 and smaller font 57 or smaller font 35 and larger font 57), the luminance levels were manipulated meaning either the larger number stimulus (i.e., 57) was presented in a faded format whereas the smaller number stimulus (i.e., 35) was presented in a bold format or vice versa (Foltz et al., 1984; Henik et al., 1982; Tzelgov et al., 1992; Cohen-Kadosh et al., 2007; Suzcs et al., 2005). The behavioral results showed that the stimulus quantity was changed by the luminance of the number stimuli. Consequently, Cohen-Kadosh et al. (2007) observed parietal brain region activities were affected by the luminance of the number stimuli. In interpreting this finding, Cohen-Kadosh et al. (2007) reported the parietal lobe might be equipped with neuronal substrates for magnitude processing even for non-spatial dimensions. In other words, the parietal lobe might be involved in the processing of visual qualities along with quantities of the number stimuli.

fMRI studies addressed above are perfectly suitable for providing information about where the activity is occurring in the brain during a number perception task (Heeger and Ress, 2002). However, fMRI is not temporally sensitive enough to measure activities that change in milliseconds. EEG is often used to investigate the neural events that underlie the timing and organization of a number perception task, especially during times when no overt behavior can be registered (e.g., when humans plan and prepare for upcoming actions). EEG is a continuous recording of the electrical activity of the brain from the skull during a certain time interval. This surface activity is influenced by the electrical activity from the brain structures underneath the skull. Each electrode site is labeled with a letter and a number. The letter refers to the area of brain underlying the electrode (e.g. P- Parietal lobe, and O-Occipital lobe). Even numbers denote the right hemisphere and odd numbers the left hemisphere.

ERP Studies and Common ERP Components of Number Comparison

Recent developments in high resolution EEG (50 or more electrodes) with temporal resolution (tenths of milliseconds) have been used to distinguish between behavior and the temporal brain dynamics. The analysis of event-related brain potentials (ERPs) from high-resolution EEG recordings is a precise method for determining the timing and neuronal organization of specific cognitive processes, especially when no overt behavior can be registered (e.g., when humans plan and prepare for upcoming actions). A common approach to understand underlying brain dynamics of cognitive processes is to analyze positive and negative ERP components. Luck (1998) defined the ERP components as scalp-recorded neural activity that is generated in a given neuroanatomical site when a specific computational operation is performed. By definition, a component may occur at different times under different task conditions, as long as it arises from the same module and represents the same cognitive function. The scalp distribution and polarity of a component may also vary according to this definition, because the same cognitive function may occur in different parts of a cortical module under different conditions. Ambiguities in interpreting ERP components are the result of task-dependent variations. Although, there is no way to prevent misinterpretations, focusing on one or two ERP components are usually tractable.

The ERP studies are focused on the parietal electrode sites based on the findings on the IPS involvement in number perception. The latencies, amplitudes, and inter-hemispheric correlations have been analyzed to understand the underlying mechanisms of visual perception and quantity judgment. Related studies were focused on a sequence of ERP components: (1) P1 is a component related to visual stimuli and observed over parietal and visual areas of the skull. Since P1 can be modulated by attention, it is often analyzed to understand the relationship between unattended (visual representation) and attended (quantity judgment) factors of the stimuli (Dehaene, 1996; Pinel et al., 2001; Turconi, Jemel, Rossion, and Seron, 2004); (2) N1 is the ERP component elicited by visual stimuli over the occipital, parietal and central electrodes. Amplitude of N1 is thought to represent selective attention (Handy, 2004), in particular the relationship between visual perception and quantitative number perception (Dehaene, 1996; Pinel et al.,2001; Turconi et al.,2004); (3) a magnitude comparison stage, affected by the distance between the reference number and the stimuli, occur over both parieto- and occipito-temporal regions on the P2p component of ERP, (4) and the late ERP components (e.g., P3) occur during motor preparation and execution stages of the quantitative number perception over the motor cortices contralateral to the response key (Dehaene, 1996). As the late ERP components are highly affected by the motor activity and muscle activities; therefore, the number perception studies have been focusing on the early components occurred within the period of 300-400 ms after the stimulus onset time (Dehaene, 1996; Pinel et al., 2001; Turconi et al., 2004; Handy, 2004). The latter limits the ability of analyzing memory components which is thought to occur after 400 ms after the stimulus onset of a number comparison task (Agam et al., 2009; Handy, 2004).

Debates on Number Processing

Considering behavioral and ERP studies, Dehaene et al. (1996) suggested that the cognitive stages, qualitative visual perception and the quantitative magnitude judgment, involved in number comparisons did not overlap with each other, and thus validated a serial stage processing trajectory starting as early as the visual identification of an N1 event. Pinel et al. (2001) and Fias et al. (2003) concluded that bilateral parietal regions might be implicated in the cerebral representations of numerical quantities independently of the visual features (e.g., quality, size, and format). This interpretation is open to questions because the same IPS sites are involved in visual perception and number perception. Therefore, it is expected that the visual presentation impacts number judgment. For example, by adding some degradation factors to the visual presentation of number stimuli (e.g., luminance; Cohen-Kadosh, 2007; noise manipulation), the behavioral response and brain dynamics would be affected. In this context, the current study addressed the visual degradation factor and challenged the conclusion of the Dehaene (1996) and Pinel et al. (2001) studies with respect to the effect of temporal engagement of visual degradation on quantity judgment.

High resolution ERPs provide task-related features; however, the data complexity and the activity recorded from one electrode can be altered and contaminated by activity from neighboring electrodes. Dimensionality reduction techniques, such as principal component analysis (PCA) and independent component analysis (ICA) are two suitable methods applied to various datasets in the literature including ERP datasets (Fukunaga, 1990; Makeig et al., 2004; Handy, 2004). In particular, PCA and ICA seek to map the activities from a high dimensional space to a low dimensional space while keeping all the relevant linear structures in the low dimensional space. In the current study, sixty-four electrode sites included in the ERP analysis were reduced to three PCs and ICs.

PCA and ICA Studies in the ERPs Literature

In the ERP literature, ICA techniques have three applications; (1) artifact reduction of EEG recordings (e.g., the low impendence, eye blinks; Makeig, Debener, Onton and Delorme, 2004); (2) spatial mapping of brain dynamics (Szucs et al., 2005); (3) source localization (Handy, 2004). However, in the ERP literature, these techniques have not been used to address the dominant temporal dynamics of ERPs together with their spatial maps. Specifically, different time points are grouped together as part of a single component to the extent that they tend to vary in a correlated manner, as would be expected for time points that reflect a cognitive process (Luck, 1998). PCA transforms a large number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component (PC1) accounts for the maximum variability in the data and each succeeding component accounts for as much of the remaining variability as possible (Pearson, 1901; Jolliffe, 2002; Fukunaga, 1990).

ICA is a statistical technique for revealing hidden factors that underlie sets of random variables, signals and measurement. ICA defines a generative model for the observed multivariate data, which is typically given as a large database of samples. In the model, the data variables are assumed to be linear mixtures of some unknown latent variables, and the mixing system is also unknown. The latent variables are assumed to be non-Gaussian and mutually independent and they are termed the independent components of observed data (Hyvarinen and Oja,, 1997, 2000; Hyvarinen, Karhunen and Oja, 2001). Hyvarinen et al. (1997) developed a MATLAB toolbox to calculate the statistical recursive ICA algorithm, FASTICA, to calculate the ICs.

In summary, the current study delves into the question: namely, whether visual attributes of numbers affect quantitative judgment. The following chapter, “a number comparison experiment”, is the main chapter of the dissertation and is prepared for future submission to a journal. The chapter starts with an introduction addressing the taskdepended factors; particularly the relationship between sensory perceptions (e.g., visual quality) and quantitative perceptions (e.g., numerical distance from a reference number). The second section (the methods) describes the participants, methods and procedures (i.e. numbers, visual noise), behavioral and ERP data analysis followed by the results. In the final chapter, the behavioral and ERP results are discussed to address the underlying mechanisms of the task-dependent factors. Appendix-I explains the initial planning of the experiment to achieve valid and reliable results for the principle study. The behavioral experiments presented herein are discussed, including preliminary comments to clarify the final task discussed in Chapter-2. Appendix-II concludes with a discussion of the preliminary ERP results and their potential inferences followed by supplementary ERP and IC images.

II. A NUMBER COMPARISON EXPERIMENT

Overview

Human perception consists of two main processes, sensory input (e.g., visual, tactile, auditory) processing and cognitive processing (e.g., quantity). In this context, the quantitative perception of visual sensory input has been used to understand the underlying mechanisms of number perception. The unattended visual attributes of the stimulus presentation (e.g., luminance, size) automatically changes the quantitative perception of the attended stimuli (Tzelgov, 1997; Tzelgov, et al., 2000). The size congruity effect is one of the common examples of the influence of the physical size of a numerical stimulus on the perceived quantity of the number (i.e., distance effect). The distance effect is defined by logarithmically increasing the RT function (Hinrichs et al., 1981; Dehaene et al., 1990) whereas the size congruity effect is defined as the interactive relationship between the physical size of the stimulus and the quantity. For example, the response time for comparing paired numbers presented as a larger number quantity with larger font and a smaller number quantity with smaller font will be faster than comparing larger number quantity by smaller font and smaller number quantity by larger font. Both distance and size congruity effects show that the sizes or quantities conveyed by numbers are processed even when completely irrelevant to the task at hand or even when they clearly interfere with processing the attended stimulus. This suggests that numerals are assigned to their internal representations instantly without any need for conscious processing.

Moreover, in their seminal paper Moyer et al., (1967) suggested that the distance between two numerals is judged similarly to the way the distance between two physical stimuli is judged (e.g., length of a line). Many researchers agree with the general notion put forward by Moyer et al., (1967) (McCloskey et al., 1985; Dehaene et al., 1992; McCloskey et al., 1992; Campbell 1994; Cipolotti et al., 1995; Dehaene et al., 1995; Noel et al., 1997) for numbers between one and nine. These studies suggested a common line for single-digit number comparison. For example, the response to indicate whether 6 is larger than 5 is slower than the response to indicate whether 9 is larger than 5. Also comparing a 15 inch line with a 10 inch line takes longer time than comparing a 25 inch line with a 10 inches line.

With two-digit numbers, the underlying mechanisms seem to change. In parallel to the single digit number comparison studies, the two-digit number perception (i.e., the distance effect) is influenced by the physical presentation of the stimulus (Ganor-Stern, et al., 2007). However, it seems that two-digit numbers may not be processed as one whole because both components of the number (the ones-place and the tens-place) are taken into account when exercising a comparative judgment (Nuerk et al., 2001; Kaufmann et al., 2005). This result suggested that making a decision of whether or not 72 is larger than 65 may take longer than deciding if 76 is larger than 65 because in 72 the tens-place is larger than the reference number. Thus, it is insufficient to process a tens-place digit (e.g.,

7) and make a decision about the numeric quantity without evaluating the second digit (i.e. 2 vs. 6) in making a judgment on quantity.

The effects of sensory visual attributes on two-digit number processing have also been studied. One of the well-studied visual attributes is the notation of number stimuli (Arabic (32) vs. verbal (thirty two) numbers) and its effects on quantity (distance) judgment (Pinel et al., 2001). Pinel et al. (2001) studied the effect of verbal versus Arabic formats on a two-digit number comparison task during a combined ERP and fMRI study. This study suggested that visual format perception and the quantity perception (i.e., distance judgment) occurred sequentially.

In the same context, Cohen-Kadosh et al. (2006) studied the effects of visual attributes on number perception controlling the luminance parameter of the visual stimulus. The latter was an alternative study to the traditional approach in size congruity studies (Foltz et al., 1984; Henik et al., 1982; Tzelgov et al., 1992; Cohen-Kadosh et al., 2007; Suzcs et al., 2005) which suggested an interaction between size congruity and the numerical quantity. The overall results suggested that there is a temporal overlap between the visual perception of number stimuli and quantity judgment and the IPS is directly involved in the processes (Ansari, 2007).

Aims and Objectives of the Study

The studies reviewed above have examined the format effect on number perception (i.e. Arabic vs. verbal numbers, lines vs. Arabic numbers), size congruity (i.e. small numbers in smaller font vs. larger numbers in larger font or vice versa), as well as other types of congruity such as the luminance effect (i.e. darker numbers smaller vs.

lighter numbers larger or vice versa). In general, these studies concluded that number quantity judgment (e.g., distance effect) can be perturbed by visual or sensory representation of the numbers (e.g., visual noise manipulation). The present study attempted to advance this research further by addressing the question of how the numerical judgment of two-digit numbers (distance effect) is influenced by visual manipulation when they are compared to a memorized reference number (e.g.,65). This study examined whether visual noise could modulate two-digit comparative judgments. Determining the timing and neuronal organization of certain cognitive processes and isolating the specific time window along with the brain regions from the whole process provided information about the effects of visual quality judgments on quantitative judgment of number stimuli.

The analysis of event-related brain potentials (ERPs) from high-resolution EEG recordings is a precise method for determining the timing and neuronal organization of specific cognitive processes, especially when no overt behavior can be registered (e.g., when humans plan and prepare for upcoming actions). A common approach to understand underlying brain dynamics of cognitive processes is to analyze positive and negative ERP components. By definition, a component may occur at different times under different task conditions, as long as it arises from the same module and represents the same cognitive function. The scalp distribution and polarity of a component may also vary according to this definition, since the same cognitive function may occur in different parts of a cortical module under different conditions. Ambiguities in interpreting ERP components are the result of task-dependent variations. The latter causes the misinterpretations of certain brain dynamics.

In this study, parietal electrodes were isolated for the analysis 300 ms after the stimulus onset to determine the relationship between visual quantity and quality factors. The latencies, amplitudes, and inter-hemispheric correlations were described within and between visual quantity and quality factors.

In addition, well-characterized ERP components were focused over parietal brain regions. The following sequence of posterior ERP components have been typically used for number comparison studies: (1) a visual attention stage (P1 component) which was suggested as the attentional influences on sensory selection over occipital regions (Dehaene, 1996; Pinel et al., 2001; Turconi et al., 2004); (2) a visual identification stage (that occurred as N1), which was affected by stimulus notation and occurred bilateral (for Arabic numerals) over occipito-temporal regions (Dehaene, 1996; Pinel et al.,2001; Turconi et al.,2004); (3) a magnitude comparison stage, affected by the distance between the reference number and the stimuli, and occurring over both parieto- and occipito-temporal regions on the P2p. Techniques such as PCA and ICA obtain the ERP components from the correlational matrix of the ERP dataset (Handy, 2004). PCA decomposes the multi-channel ERP data into a set of orthogonal basis functions, whereas ICA separates the data probabilistically, evaluating the independence of the decomposed components (Handy, 2004). These two approaches, PCA and ICA, will be used to cluster the electrode activities recorded during the specific process along with spatial map (topography) of brain activity. This is suggested as an alternative to the more common clustering and topographic ERP analyzing methods (Murray, Brunet and Michel, 2008).

Hypothesis and Predictions

The hypothesis for this experiment was that the visual quality of the stimuli affects quantitative distance judgment. This hypothesis was tested by examining the behavior and brain dynamics recorded during performance of a number comparison task. Behavior was analyzed by measuring task RT and accuracy whereas the ERP components reflect the neural activity that corresponds to the temporal involvement of the visual quality and quantity of the number processing. Consequently, we predicted that posterior ERP components, N1, P2p and N2, occurring during the time interval 300 ms after stimulus onset provide information about the relationship between quality and quantity processes as: (1) the amplitude of N1 peak would decrease with visual noise, (2) the magnitude of P2p would increase with visual noise, (3) the interactive noise and distance effect between P2p and N2 peaks would be observed for visual noise added stimuli.

Predicted Perception Model

The current study modified the model by Pinel et al. (2001) during a two digit number perception task. Pinel et al. (2001) examined the format effect on distance judgment in an additive factor method (AFM) design assuming that format and distance judgments are sequential and independent processes. The rationale underlying the AFM method is that by systematically changing a variable, a specific stage of the processes could be differentiated. Systematically examining the parameters will provide a valid task to understand the stages and their relationships. Because task variables influence specific cognitive or behavioral processes, the observed effects of variable manipulation can be interpreted more precisely in terms of function or related structure. If manipulation of two-task variables shows additive effects (e.g., if they do not interact), they are assumed to influence different processes.

The object of the present study is to determine the influence of visual quality on the perception of numerical quantity (i.e., distance from a reference number). Since the visual quality and quantity engage in temporal domain, AFM is predicted as a suitable model to investigate the interactions. However; the cavity of AFM is that task performance is assumed as the sum of sequential and independent processes. The current study proposed that visual quality and quantity processes are organized in a sequential order; but exhibit dependent processes. In other words, the visual quality process begins first and before it is completed, the quantity process begins. In this context, Figure II-1 shows the predicted perception model of the two-digit number comparison task. The first stage is stimulus identification (quality) performance changes by the visual noise factor F (d). Then, the second quantity judgment is affected by semantic distance from 65, represented as F (l). The stage indicated by the circle identifies the interaction between the first stage, F(d) and the second stage F(l). For example, if we know the RT for F (0), F (0.60) and F(0.75) of close numbers, F(close), it might be possible to calculate the noise parameter ($nf_{0.60}$) as RT (0.60, close) = RT (0, close) + $nf_{0.60}$ and RT (0.75, close) = RT (0, close) + $nf_{0.75}$. Our hypothesis is that $nf_{0.60}$ and $nf_{0.75}$ are not proportional to the noise. Therefore, there is an interaction between visual quality and quantity. Moreover, the latency and magnitude values of certain ERP components, N1, P2p and N2 provide the brain dynamics of the behavioral responses reflecting the behavioral data In other words, N1, P2p and N2 are not predicted to be proportional within the noise factor and will change the characteristic across the noise factors. Consequently, PCA and ICA are predicted to represent the ERP components on a reduced dimension (i.e., 3). In addition, these methods will provide the topographic map of the overall number perception within the period of 300 ms. after stimulus onset time.

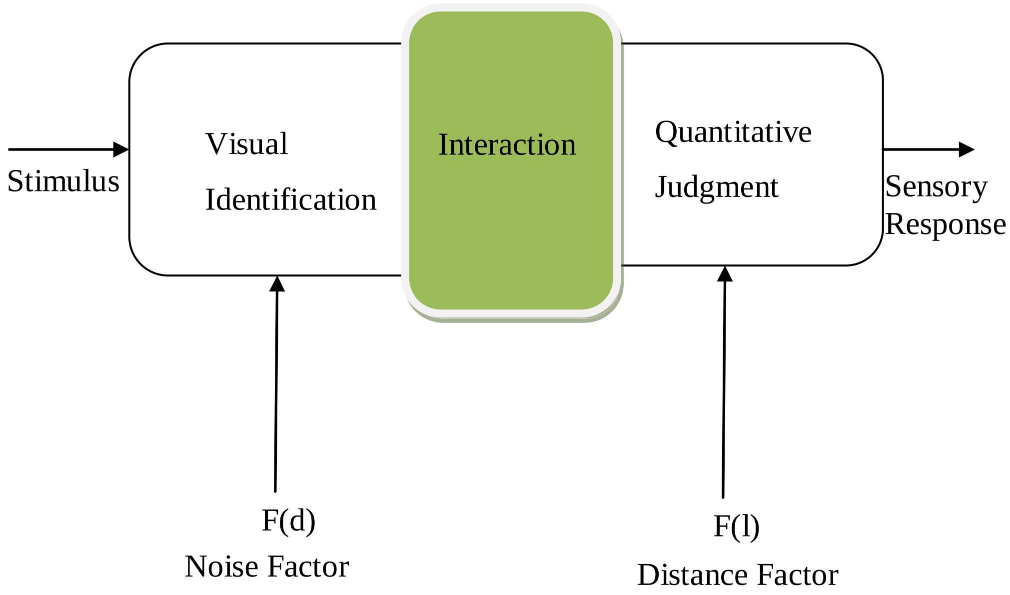


Figure II-1 A model of the processes involved in the number comparison task. The first step is to identify the visual features of stimuli (noise added or not). The center circle represents the cognitive process that occurs in parallel with quality and quantity judgment. The judgment of relative number quantity is what happens during the circled period.

Methods

Participants

The study participants were fifteen right-handed, neurologically normal young adults (four females and eleven males between the ages of 18 and 30 years) with normal vision. All participants gave their informed consent and were randomly selected from the voluntary participation database of the University of Groningen. Three participants were rejected from the analysis because of excessive eye movement artifacts. The average age for the twelve remaining participants was 26.4 years with a standard deviation of 3.8 years. The Ethics Committee of the University Medical Center Groningen, the Netherlands, approved the study. The first language criterion of the participants was not included in the research proposal. Therefore, we did not have access to the first language information. However, it was known that all of them were Western European who learned to write from left to right.

Number Comparison Task Procedure

The e-Prime psychology toolbox was used to develop the task because of its ability to present, synchronize and collect the data in milliseconds. All participants performed the same task that was simply constructed from 24 Arabic numbers, whereby they selected pseudo-randomly among 69 numbers occurring between 30 and 99. First, the numbers were classified into two groups: those larger than 65 and those smaller than 65. Then they were labeled as close numbers (60 - 64 and 66 - 69), intermediate numbers (50 - 59 and 70 - 79) and far numbers (30 - 49 and 80 - 99), according to their semantic distance from the reference number 65 (Table II-1). When the stimuli were selected, a pair-wise equal sample procedure was followed, meaning that the larger four numbers from each distance condition were randomly picked from the 34 numbers between 66 and 99, and smaller numbers were selected equally distant from the reference numbers.

Subsequently, two levels of visual "salt and pepper" noise were added to degrade the visual recognition process. The salt and pepper noise is typically seen in familiar images (i.e., on a TV screen, computer screen, pictures taken with a dusty objective, CCD faults of digital camera, etc.). This very familiar noise, represented as randomly occurring white and black dots, presents an underlying idea that noise limits the visual perception sensitivity; but it does not block the quantitative perception totally (Pelli and Farell, 1999). A MATLAB function, imnoise, was chosen to define three visual noise density level d : no-noise (d = 0), medium-noise (d = 0.60), and dense noise stimuli (d = 0.75; Figure II- 2).

The number stimuli were presented to subjects at the center of a 15-inch, 100 Hz computer screen in random order, and were presented in "Arabic Arial Font" in 256 x 256 image size.

The task commenced with an instruction slide presented for 30 s, followed by a practice block containing 72 trials, concluding with the experimental task, consisting of four trials to synchronize systems and six blocks with pauses after every 72 trials (Figure II-3). In addition to instructions given verbally, the task began with an instruction slide; "The task will start in 30 s. You will see two-digit numbers with or without visual noise degradation on the screen. Please compare the presented number with a memorized reference number 65. Please note that 65 will not appear during the task. Please press the left button for smaller numbers and the right button for larger numbers as soon as you see the numbers. Thank you very much”. The language (either Dutch or English) of instruction changed according to the subject’s preferred language.

The number stimuli remained on the screen until a response was given, or in the case that a response was not given, the stimuli disappeared automatically after 2000 ms. Inter-stimulus interval (ISI) time varied between 3 and 5 s, with steps of 182 ms. The subjects were not provided with any feedback regarding their responses. Task parameters were validated before the final task was presented.

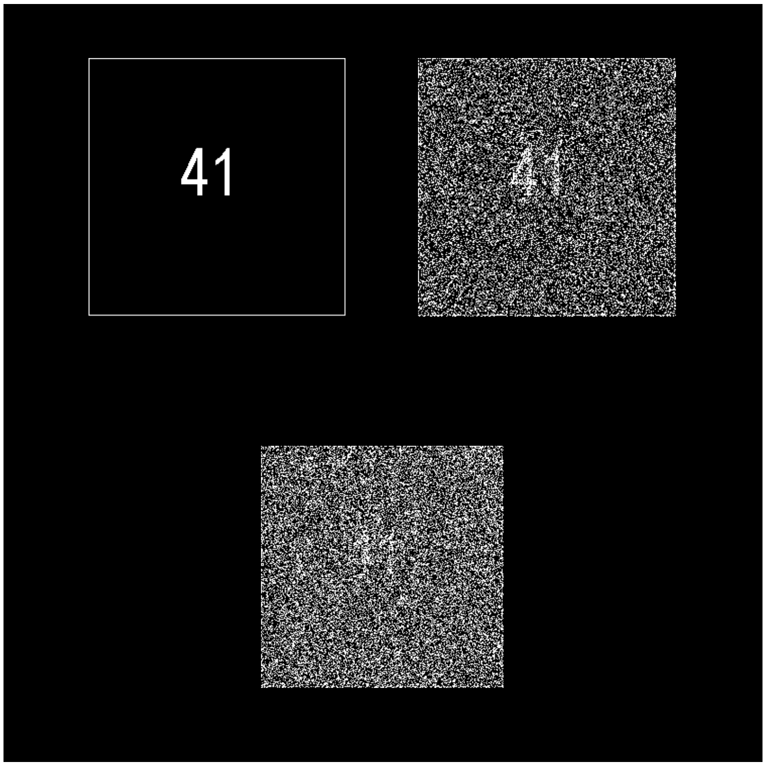


Figure II-2 Representative example of the number stimulus presentation and the manipulation of visual quality. Upper left: d = 0, no-noise; upper right: d = 0.60, medium noise; bottom: d = 0.75, dense-noise added stimuli. Each stimulus was presented as a white Arabic numeral.

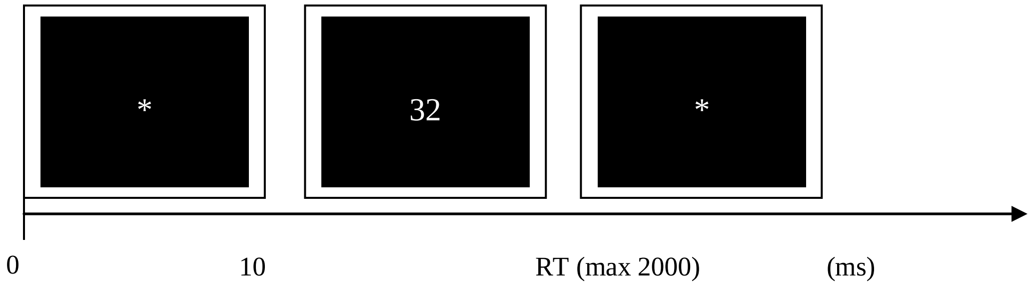


Figure II-3 Example trial from the two-digit number comparison task. The average inter-stimulus interval was 4 s. (max ISI=5 s and min ISI=3 s) in steps of 182 ms. The trial was initiated with the presentation of a fixation asterisk for 10 ms. Next, the number stimulus appeared on the screen and the subject had up to 2000 ms to respond on the right or left response key. Once the participant made their response the number stimulus presentation was terminated. If the response was not given within 2000 ms, then the program terminated the stimulus presentation. The last fixation asterisk was presented during the remaining period of [ISI-(RT+10)] ms.

Table II-1 Numbers that were chosen for the two-digit number comparison task.

Distance	Condition Smaller	Condition Larger	Noise Manipulation
Close	61-62-63-64	66-67-68-69	No, Medium, Dense
Medium	51-52-54-56	74-76-77-78	No, Medium, Dense
Far	32-38-41-48	82-90-92-98	No, Medium, Dense

EEG Recording and Data Acquisition

Continuous EEG was recorded from 64 scalp sites, using electrodes attached to an electrode cap (ElectroCap International) located over the frontal, central, parietal, occipital, and temporal areas of both left and right hemispheres. The electrodes were referenced to linked earlobes. An electro-oculogram was used to detect blinks and eye movements with the ground electrode placed on the chest; two electrodes were placed on the outer canthi of both eyes and above and below the right eye. The electrode impedance level was adjusted to below 10 kOhms. The EEG data were recorded using the Brain Vision Recorder of Brain Products GmbH. The brain signals were amplified with a band-pass set up of 0.01-30 Hz and digitized at 100 Hz.

Obtaining the RTs

After positioning the EEG electrode cap on the skull, the subjects were seated in a dimly lit room and responded to test stimuli by pressing one side of a two-sided button box, the left hand side button for numbers smaller than 65, or the right hand side button for larger numbers.

Data Analyses

Behavioral Data

The design parameters were visual quality (no, medium and dense noise), number quantity (distance from memorized reference number 65, as close, medium, and far distance numbers) and condition (smaller or larger than the reference number). The average correct RTs measured during the ERP recording were computed for each participant and were analyzed using repeated-measures ANOVA. Errors and missed answers were also computed for each condition and analyzed. Errors are the wrong button presses (e.g., the larger numbers than reference number, 65 were responded by left hand) and the missed answers are the trials terminated by program (i.e., if there is no answer in 2000 ms after the stimulus onset, the trial is terminated by the program). The errors and missed answers were excluded from the analysis since the number of data sets was not enough for statistical analysis.

ERP Data

The Brain Vision Analyzer of Brain Products GmbH was used to analyze the ERP data. Trials containing ocular artifacts, movement artifacts or amplifier artifacts were excluded from the ERPs by applying the following algorithms. The procedure applied to each dataset consisted of band-pass filtering between 0.2 Hz and 30 Hz at 48 dB/Oct. Eye movement artifacts were corrected using the Gratton and Cole's method (1983). Subsequently, ERP datasets were segmented individually according to size (smaller or larger), distance (close, medium, far), and noise conditions ($d = 0$, $d = 0.6$, and $d = 0.75$). A baseline correction was performed with a time interval of 100 ms prior to stimulus onset, and was averaged for each participant. The visual quality influence on quantity comprised the area of interest, thus the time window of 300 ms after stimulus onset time was included into the analysis. The electrode positions are shown in Figure II-4. The parietal, occipital and temporal electrodes were isolated to analyze the IPS regions. The P1 components were computed as the mean amplitude in a window of 80 - 120 ms, on parietal-occipital-temporal electrodes (P3/P4, PO7/ PO8, O1/O2, POz, and Oz), with a negative counterpart on Fz. N1 was computed similarly in a 130 – 170 ms time window on parietal-occipital sites (P6, P3/P4, PO7/PO8, PO9/PO10, and O1/O2), accompanied by the negative central counterpart Cz.

The second posterior positivity component is P2p, which was measured on similar parietal-occipital-temporal regions as P1 (P3/P4, PO7/ PO8, PO1/PO2, POz, and Oz), with a negative counterpart on CPz and Cz. The time window was 170 - 210 ms following the stimulus. The next component, N2, was measured in the time window of 240 - 280 ms over (P6, P3/P4, PO7/PO8, PO9/O10, and PO1/O2). In order to extract the features of the particular number comparison task, PCA and ICA were chosen. PCA/ICA provided correlational structures (or eigenvectors) of ERPs, as the different time points were expected to reflect a common cognitive process along with the spatial representation of these two methods.

The MATLAB singular vector decomposition (SVD) method was used to perform PCA. There are many algorithms performing ICA on a similar basis, and we have chosen FASTICA toolbox for MATLAB (Hyvarinen, et al., 1997, 2000, 2001). These two comparative models of data decomposition provided a unique and rapid procedure to extract the most significant characters of brain dynamics during our task. Our study is the first study using ICA and PCA techniques together to identify the similarity and differences between ICs and PCs.

The mean electrode amplitudes were submitted to repeated-measures ANOVA in the designated time windows, including those for the ERP components above (Handy, 2004). The task parameters were visual quality and quantity. The averaged peak values and latency of the ERP components were statistically compared to calculate the statistically significant values. The Spherical Greenhouse and Geisser formula was used for all effects and interactions with two or more degrees of freedom. Degrees of freedom were computed before the exact p-value adjustments with the sensitivity of $p<0.05$. The PCA and ICA components were also submitted to a repeated measure ANOVA. Thus, instead of discussing the regional electrodes, we analyzed the PCA/ICA components to discuss regions involved in the two-digit number comparison tasks during 300 ms following the stimulus onset.

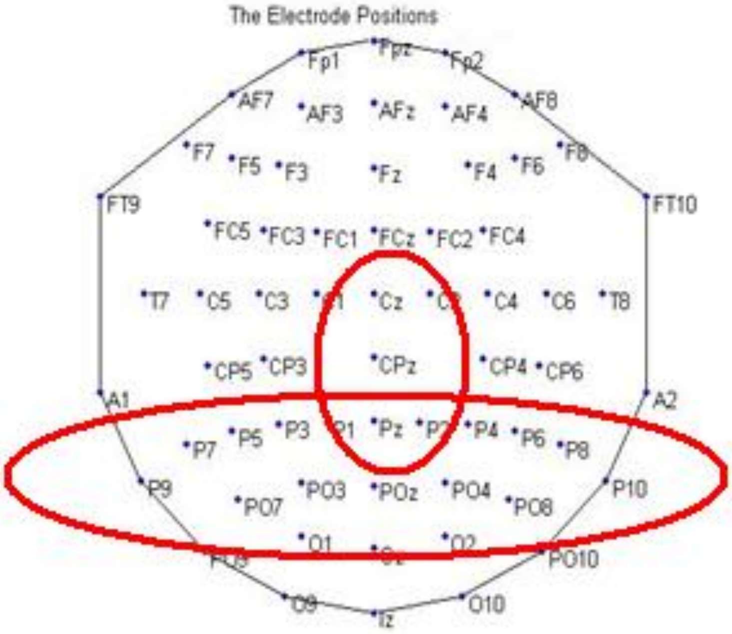


Figure II-4 A flattened representation of the high-density EEG (64 electrodes) electrode locations. O1/O2, P3/P4, PO7/ PO8, O9/O10, P6/P5, POz, Oz, CPz, Cz, and FPz were the electrodes included in the analyses. Front of the head is towards the top of the image.

Results

The Result section is divided in three subsections. The behavioral results are presented first, followed by the ERP results which are organized into two subgroups. A general description of the analysis is presented before the results (in addition to Table II-2 which summarizes the statistical results). The second part includes the statistical results. The ERP results section is followed by the PCA/ICA analysis.

Behavioral Results

The mean error rate was sufficiently low (6%) since there were not enough events to warrant statistical analysis. Participants were non-responsive within 2000 ms in only 1.5% of the trials conducted herein which is not sufficient enough to test the statistical significance.

There was no main effect due to reaction sides (left-hand button pressed for smaller numbers, right-hand button pressed for numbers larger than 65 ($F < 1$). This finding supported the SNARC effect because although the participants responded with their right hand for larger stimuli and with their left hand for stimuli smaller than the reference number(65) and all participants were right handed, there was no-bias of right-handedness (Dehaene, 1996). Therefore, the reaction side (i.e., left or right) factor was omitted from further analysis. The RTs for the numbers smaller and larger than the reference number of 65 were averaged together to increase the sample size.

There was a significant main effect of noise ($F (2,22) = 59.23$, $P < 0.05$) revealing that mean correct RTs were significantly longer for processing dense noise added numbers (RT_{dense}=1126 ms) compared to no-noise added numbers ($RT_{nonoise}$=664 ms) and also in comparison to medium noise added numbers (RT_{medium}=896 ms).

The main effect of distance was also significant (F (2,22) = 69.9, $P < 0.05$). Post-hoc analysis revealed a significant difference in RT between close and far numbers (RT_{close}=1208 ms, and RT_{far}=775 ms) while RTs for far and medium numbers did not differ significantly ($RT_{medium=}$788 ms). In addition, the interaction between distance and visual quality (noise) effects was significant (F (4,44) = 18.6, $P < 0.05$) showing that close distance numbers are more affected by noise manipulation. Moreover, the marginal RTs were recorded for far numbers in the dense noise condition, reporting an interaction between visual quality (noise) and quantity (distance) effects (F (1,11) = 21.5, $P < 0.05$; Figure II-5). Specifically, figure II-5 shows a more pronounced visual noise effect on close numbers ($RT_{closenonoise}$=660 ms, and $RT_{closedense}$=1222 ms). The main effect of visual manipulation was significant for further analysis performed between far and medium distance number stimuli (F (1,11) = 109, $P < 0.05$). The post-hoc analyses showed a significant difference in RT between dense and no-noise added number stimuli (Figure II-6). Surprisingly, the RTs for visually manipulated stimuli increased the order of far, close and medium numbers (e.g., RT of medium noise and medium distance condition < RT of medium noise and far distance condition).

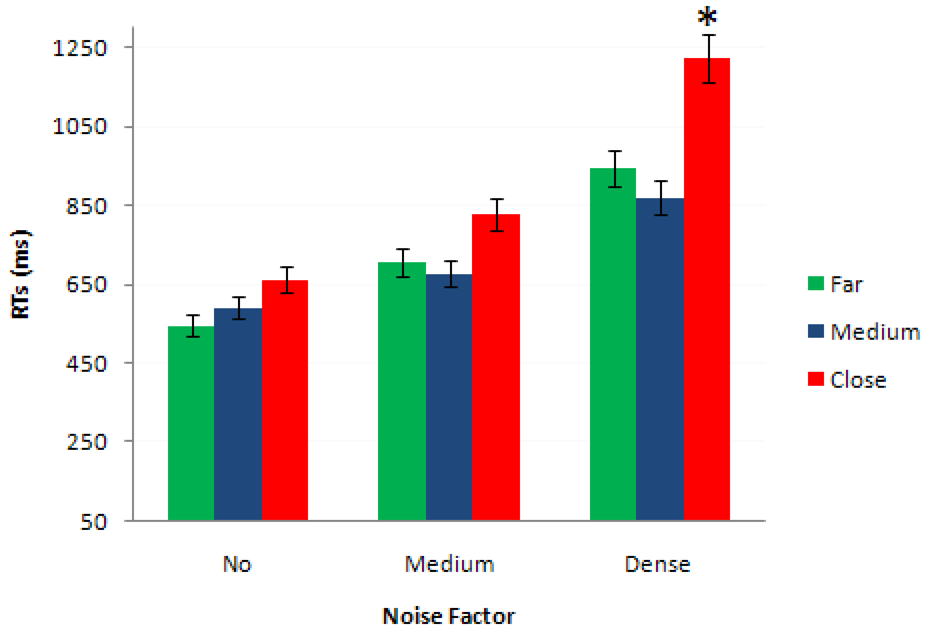


Figure II-5 Averaged reaction times of EEG participants. The RTs are reported as an increasing trend with increasing noise manipulation for each distance group. The difference between the RTs of far and medium distance number stimuli was not statistically significant. The latter suggested that the visual quality influences on the perception of number quantity. * represents a significant interaction between visual noise and distance factors ($p<0.05$)

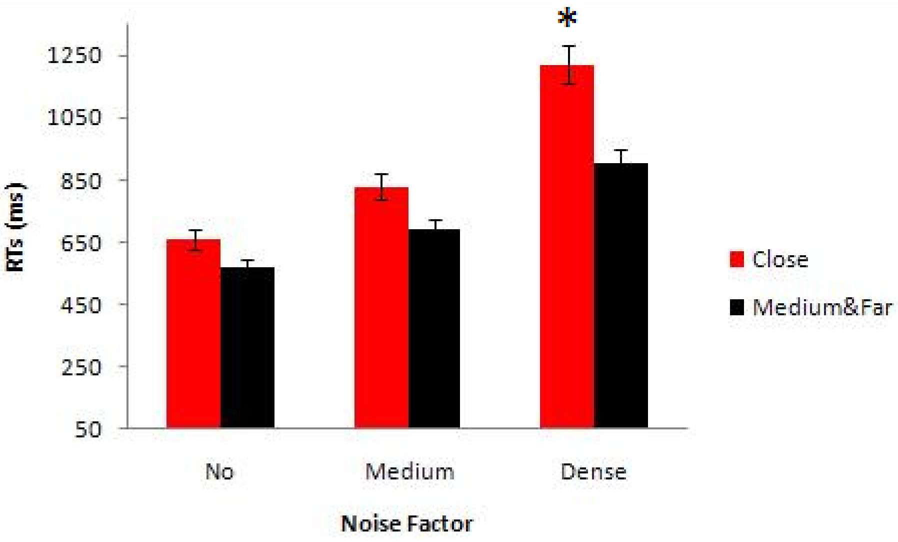


Figure II-6 The RT comparison between close and averaged medium and far distance stimuli. A significant effect of interaction between noise and distance was reported for close distance-dense noise added stimuli.

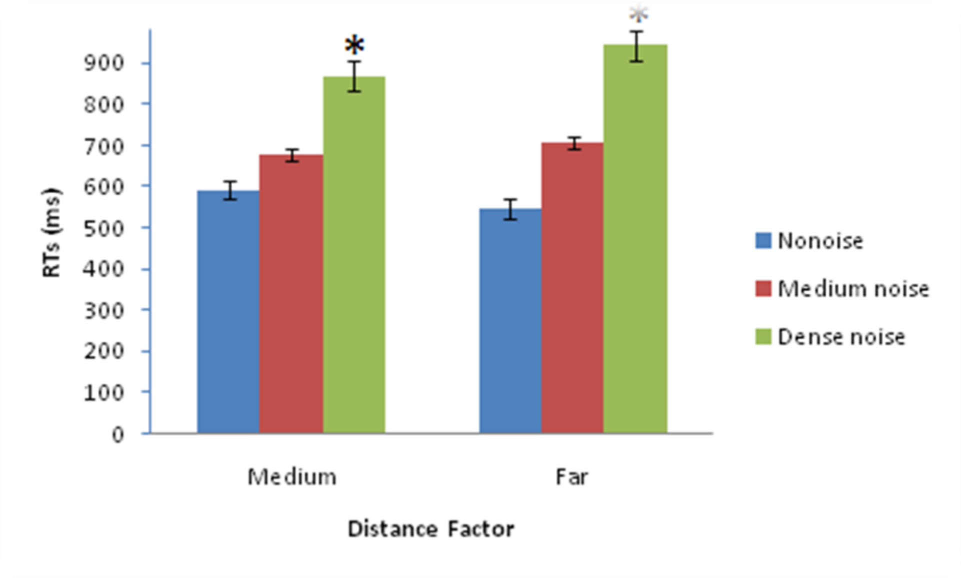


Figure II-7 The RT comparison between medium and far distance stimuli. The RTs for far distance number stimuli were slightly larger than medium distance number stimuli. The RTs for medium noise added stimuli was not changed by distance effect.

ERP Results

Two point eight percent of the trials were excluded because of artifacts along with 6% of the trials excluded due to wrong and omitted answers (see the behavioral results). The average number of trials included in analysis was calculated as 420 per subject.

Five major ERP events that occurred during the first 300 ms after stimulus onset were identified: 1) the first positive deflection at posterior sites, the P1, observed around 100ms for all three visual quality (noise) conditions over left and right parieto-occipito-temporal electrodes; 2) a negative bilateral temporo-parietal component, N1, peaking around 137 ms as a large negativity for no-noise added stimuli and as the drop for noise added stimuli from the P1 peak; 3) a second posterior positivity over parieto-occipital sites, P2p, peaking around 150 ms for medium noise added stimuli and around 165 ms for the dense noise stimuli, whereas it is observed as the change in slope for no-noise stimuli; 4) a second negativity over fronto-central sites, N2, peaking around 175 ms for medium noise added stimuli and around 200 ms for dense stimuli, and, finally, 5) a positive increase over parietal sites accompanied by central sites around 300 ms was observed for all visual quality conditions.

Figures II-7, 8 and 9 show some isolated electrodes representing the characteristics of the particular number comparison task. The main focus is parietal electrodes; however, the counter electrode dynamics also play a role during mental number comparison. Therefore, we included some central electrodes to understand the central activities (Figure II-8). More electrode activities are provided in Appendix II.

First Posterior Positivity: P1 (100 ms - 130 ms)

The second observed ERP component was P1 over the bilateral posterior electrodes (P7/P8, P5/P6, PO7/PO8, PO5/PO6, and O1/O2), accompanied by central frontal negativity (Cz/Fz). The P1 peak was observed around 104 ms and 122 ms for no noise and noise added stimuli, respectively. A main effect due to the visual quality (noise) was determined ($F (2,22) = 53.09, P < 0.05$) over POz, Pz, PO8, and PO9. Post-hoc analysis showed a significant difference between dense noise and no noise stimuli, but no significant difference between dense and medium noise stimuli. There was no significant distance effect on the bilateral posterior regions ($F < 1$) within noise added stimuli. The main effect of visual quality and quantity interaction was significant ($F (4, 44) = 50.62, P < 0.05$). Post-hoc analysis showed that this effect occurs between close and far numbers, whereas there was no significant difference in P1 between far and medium distance numbers. The P1 amplitude revealed a statistically significant hemispheric asymmetry over P3/P4 ($F (1,11) = 8.9, P < 0.05$).

First Posterior Negativity: N1 (130 - 160 ms)

The following component of observed ERPs was N1 at 140 ms following the stimulus onset over the occipito-temporo-parietal junctions (Figure II-7 and Appendix II), accompanied by central frontal positivity (Cz/Fz) shown in Figure II-8. There was no time delay of N1 components between noise -added and the no noise added (no latency). The main effect of visual quality was significant ($F (2,22) = 17.104, P <0.05$). This significance determination was related to no noise and to dense noise effects according to the post-hoc analysis. There was no significance determined between the dense and medium noise effects (F < 1). The main effect of distance was significant (F (2,22) = 23, P <0.05). The main interaction effect of quality and quantity was reported (F (4,44) = 40.7, P <0.05) (Figure II-7). For no-noise stimuli, the distance effect was significantly different between close and far stimuli whereas there was no significant difference between medium and far stimuli.

Second Posterior Positivity: P2p (175 ms)

A second focal posterior positive component, P2p, was observed for noise added stimuli (i.e., medium x dense) over P7/P8, P5/P6, P3/P4, PO7/PO8, PO5/PO6, PO3/PO4, and O1/O2 (Figure II-8 and Appendix II). Repeated-measures of ANOVA reported a significant visual quality (noise) effect (medium x dense; F (1,11) = 19.5, P < 0.05). There was an interactive noise (i.e., medium x dense) and distance effect (i.e., close x medium x far) for P2p (F (2,22) = 24.7, P < 0.05). The distance effect was most significant for the medium distance stimuli (F (2,22) = 18, P < 0.05), whereas it was not significant for dense noise stimuli (F<1). P2p tended to be larger over the right hemisphere than the left hemisphere. The results of P2p analysis suggest that the visual quality of the stimuli manipulated the distance. This manipulation was increased by the decreasing quality of the stimulus appearance.

Second Fronto-central Negativity: N2 (180–250ms)

Following the P2p, a second negativity (N2) was observed for noise added stimuli over fronto-central sites accompanied by a frontal positive counterpart, FCz. This negative component was significant for distance effect (i.e., close x medium x far; F (2, 22) =10.33, P < 0.05). The significant distance effect was in the direction of close and far distances number stimuli, whereas there was no significant effect on distance between far and medium distances. The latency, in the steps of 5 to 20 ms, over the right hemispheric sites interpreted as distance effect. The steps were larger for dense noise indicating an interaction between visual quality and quantity. P2p occurred during medium and dense noise added-stimulus representation. The interaction between visual quality and distance was statistically significant at medium and dense noise levels.

The Late Posterior Positive Component

Repeated-measures ANOVAs within the window of 270 ms and 300 ms showed a significant main effect of distance ($F(2,22) = 9.98$, $P < 0.05$) over PO7/PO8 along with midline electrodes, specifically Cz (Figures II-8, and 9 and Appendix II). The significant effect of distance was between close and far stimuli; however, there was no significant difference determined between medium and far stimuli. A statistically significant main effect due to visual quality (noise) was reported over the same electrodes ($F(2,22) = 10.03$, $P < 0.05$). Post-hoc analysis showed significant differences for each visual quality factor. There was no interactive visual quality and noise effect at this time window frame ($F < 1$).

Table II-2 summarizes the overall statistical analysis of ERPs along with a brief description of the particular ERP component discussed above.

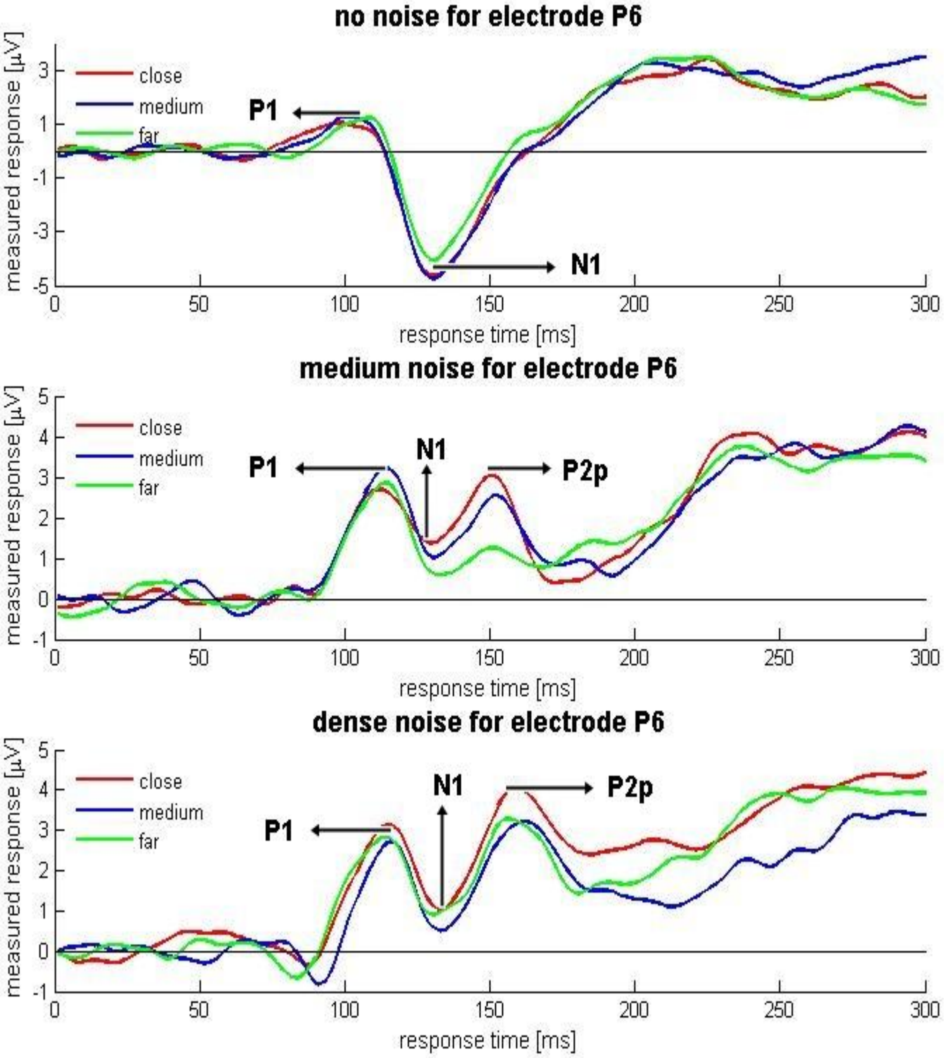


Figure II-8 Noise modulation of P6 electrode. The upper first dynamic (no-noise) is consistent with previous findings of Dehaene's findings for Arabic digits (1996), however, the dynamics change with different levels of visual noise (d = 0.60 and d = 0.75, respectively). The delay of P2p was modulated by the noise whereas the magnitude values of P2p modulated by distance within the noise groups.

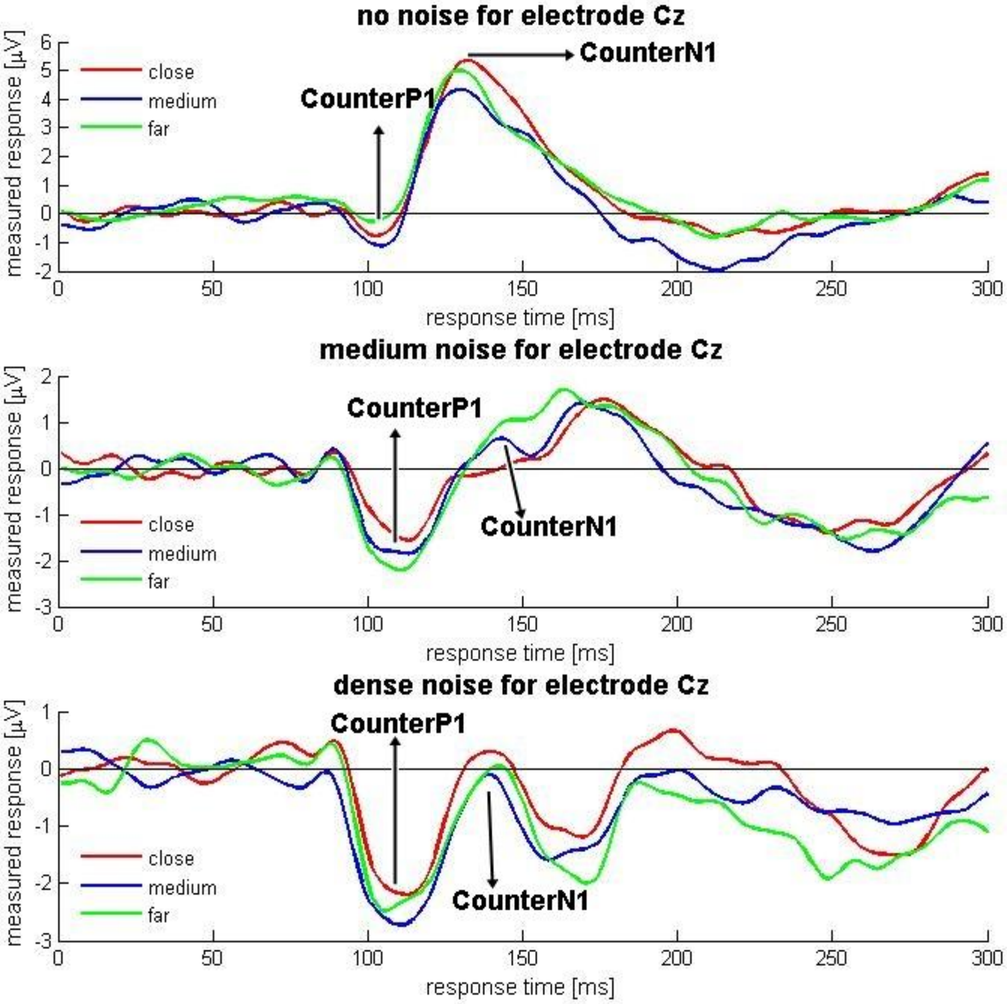


Figure II-9 Central posterior electrode (Cz). The upper first dynamic (no-noise) is consistent with Dehaene's findings for Arabic digits (1996). However, the dynamics change with the different levels of visual noise (medium and dense noise conditions, respectively). The larger distance effect was observed in the dense noise condition around 170 ms after stimulus onset time.

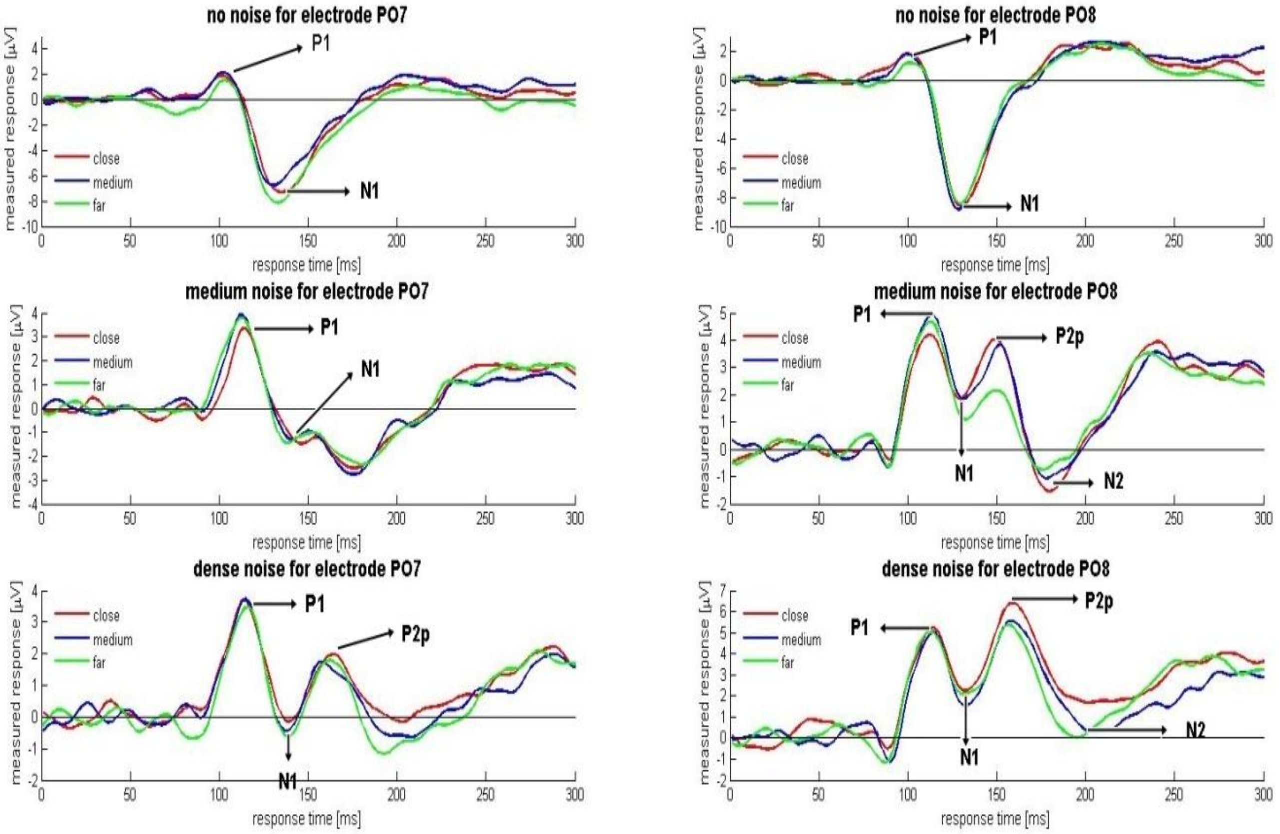


Figure II-10 Hemispheric brain dynamics of PO7 (left) /PO8 (right). The P2p component observed over the left hemisphere was increased by increasing visual noise manipulation. The increasing distance effect was also observed on these electrodes around 180 ms after stimulus onset time.

Table II-2 Summary of statistical significance of ERPs

ERP Component	Latency (ms)	Significance	Delay (ms)	Noise-Distance Relationship
P100	100-130	p(noise) <0.05	15	$P100_{noise}$-$P100_{nonoise}$
N1	130-160	p(noise x distance) <0.05	N/A	$N1_{noise}$-$N1_{nonoise}$
P2p	160-180	p({medium,dense} x noise) <0.05	10	$P100_{dense}$-$P100_{medium}$
N2	180-250	p({medium,dense} x noise) <0.05	5-20	Delay changes by distance and noise
Posterior positivity	225-275	p({close,far}) <0.05 & p(noise) <0.05	20-35	$P_{mediumnoise}$-$P_{nonoise}$ $P_{dense-}P_{medium}$

PCA and ICA Results

The orthogonal eigenvalues and eigenvectors of PCA were calculated to determine the spatial and temporal characteristics of the three largest eigenvectors, shown in right side of Figures II-10, 11, and 12. The eigenvalues of PCA were normalized to 100 to represent the percentage of data reconstructed by PCA. The largest of the three eigenvalues of the PCA were 43.6, 40.5, and 9.2, representing PC1, PC2 and PC3, respectively. We used 64 electrodes as the independent sources for ICA analysis, and 94% of data was reconstructed by FASTICA algorithm. The activities discussed are the activities larger than 0.1 (see the colorbar on the right side of the Figures II-10,11, and 12). Figure II-10 shows the parietal activities with similar ERP peaks to the individual electrodes as P1, N1 and in addition to these two components P2p and N2 for noise added stimuli. The spatial map of PC1 exhibits bilateral activity whereas the activity carried by IC1 is left hemispheric. Figure-II-11 represents posterior central electrode activities. Figure II-12 shows mainly the left hemispheric activities of PCA and ICA. The largest PC and IC components carried the posterior activities which were discussed in ERP results section. The other two components of these two algorithms represented the mixed activities of the central, temporal and parietal regions. For that reason, those components did not carry a particular ERP activity rather represented the spatial map of the activities.

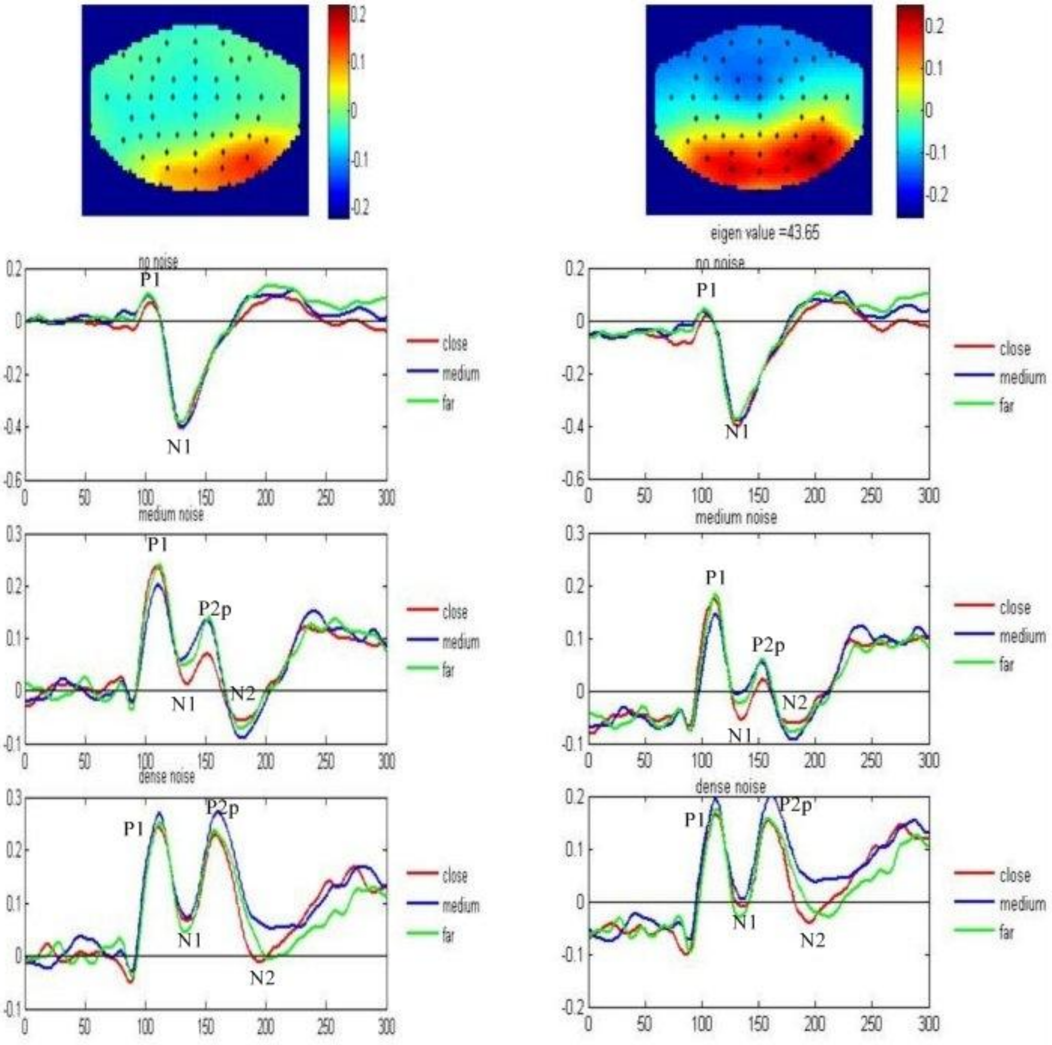


Figure II-11 Temporal and spatial dynamics of largest IC (left) and PC (right) shown with an eigenvalue) during the first 300 ms period of brain dynamics. Although the peak values are not referred to as ERPs, the first positivity around 100 ms looked similar to P1 followed by N1 around 140 ms after stimulus onset time. Parallel to the ERPs P2p was observed around 150 ms for medium noise and 170 ms for dense noise followed by N2 around 180 ms and 200 ms after stimulus onset time.

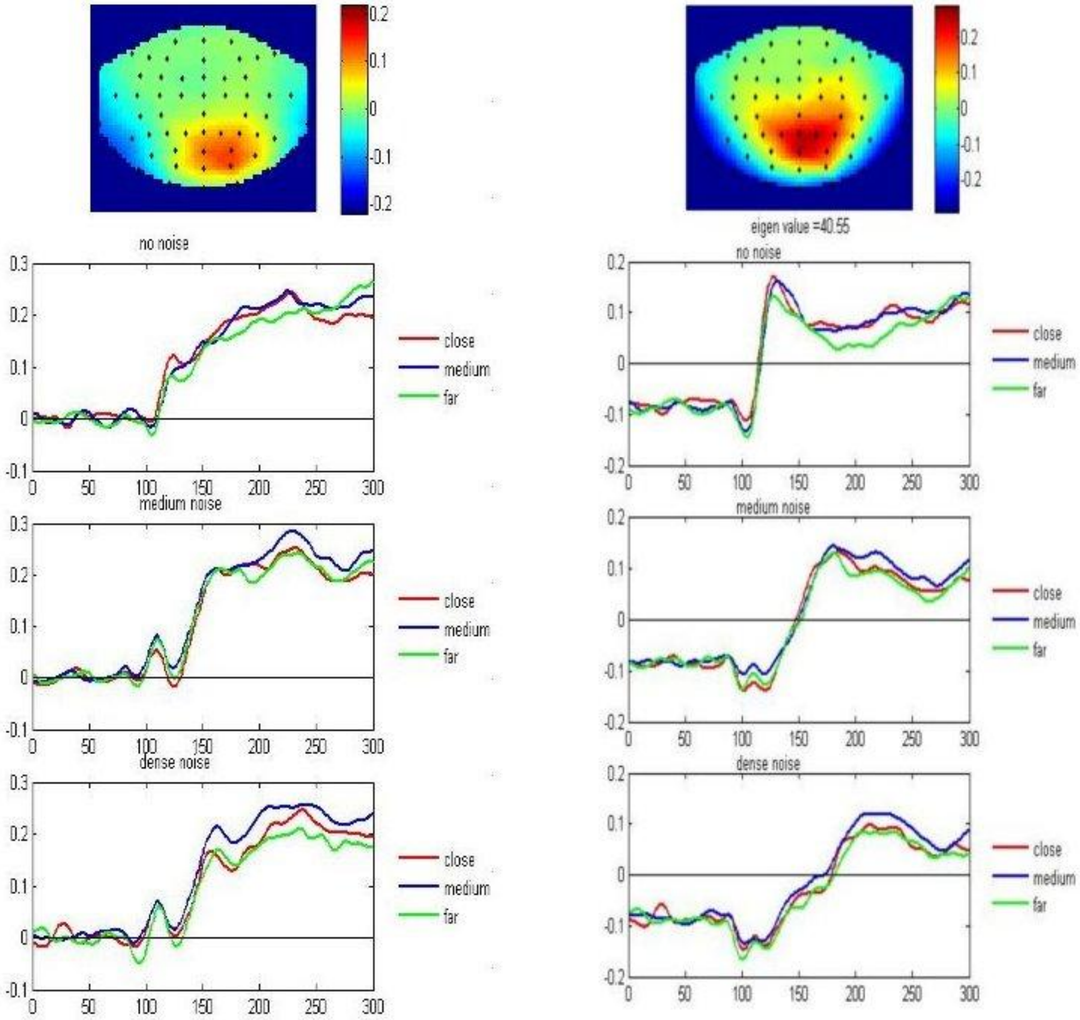


Figure II-12 Temporal and spatial dynamics of the second largest IC (left) and PC (right with an eigenvalue) during the first 300 ms period of brain dynamics.

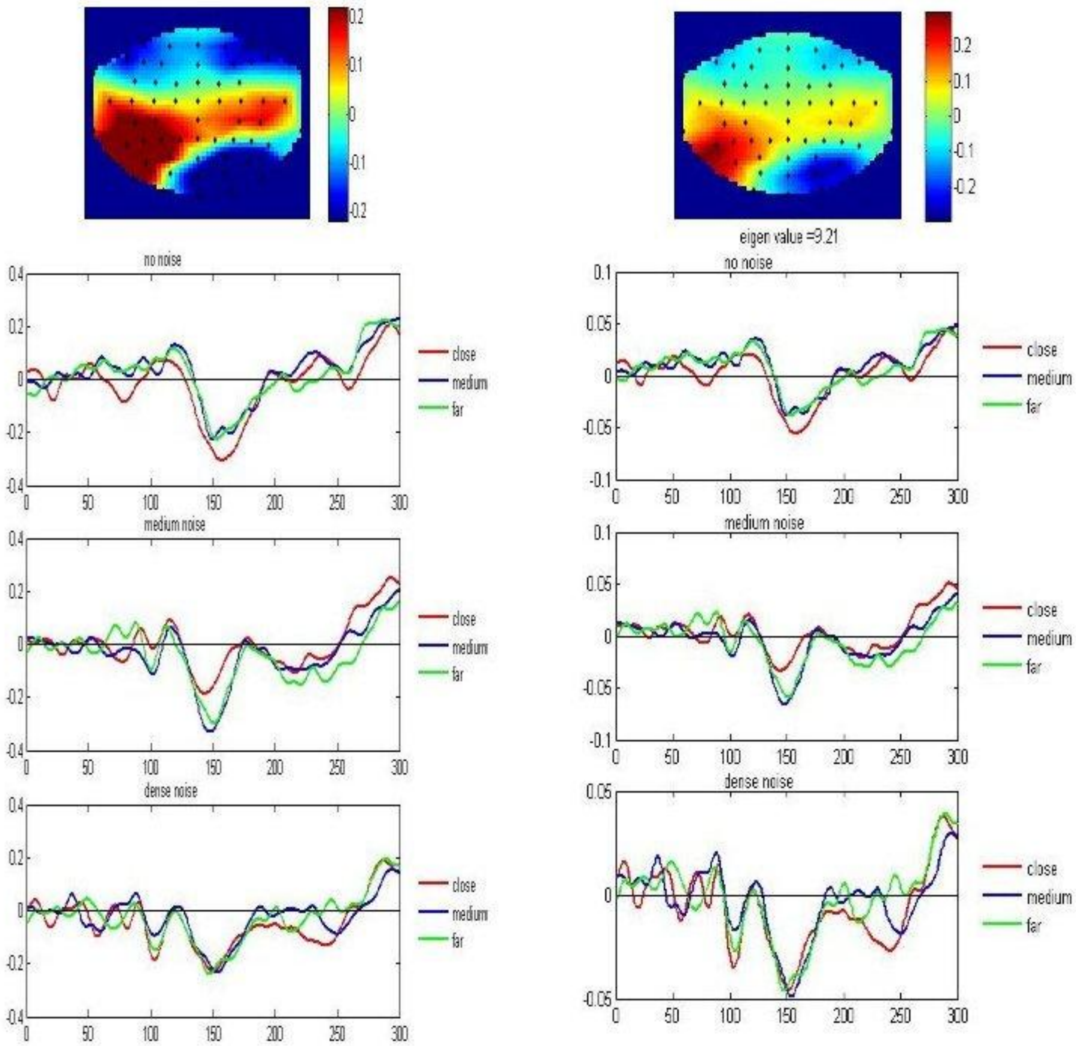


Figure II-13 Temporal and spatial dynamics of the third largest IC (left) and PC (right with an eigenvalue) during the first 300 ms period of brain dynamics.

Table II-3 Results of the ICA and PCA.

Method	MATLAB Toolbox	Eigenvalues (EV)			Decomposition (%)	Steps		
		EV1	EV2	EV3		IC1	IC2	IC3
PCA (right)	SVD	43.65	40.55	9.21	93.41			
ICA (left)	FASTICA				94	13	14	2

Statistical Analysis of PCA/ICA

In this section, PCA and ICA components of ERPs were statistically analyzed using ANOVA.

The results are summarized in Table II-4, 5, and 6. Table II-4 sums up the largest PC and IC components statistical values. Tables II-5 and 6 present the statistical results for PC2 and IC2 and PC3 and IC3, respectfully.

Statistical Analysis of PCA Components

Table II-3 illustrates that first three components of PCA accounted for 93.41% of the ERP data represented by electrodes shown in Table II-2. It is sufficient to use these three components, PC1, PC2 and PC3, which representing the largest three eigenvalues to discuss spatial and temporal statistics of ERPs.

PC1

First Posterior positivity

Analysis revealed a significant interaction of the visual quality and distance interaction (noise x distance) occurring around 100 ms following stimulus onset time ($F(4,44) = 5.15$, $P < 0.05$). Subsequent analysis revealed a significant difference between dense noise and close distance ($F(1,11) = 13.2$, $P < 0.05$). The post hoc analysis also revealed a significant difference between no noise and dense noise added stimuli. There was no significant effect determined between medium and dense noise stimuli.

First Posterior Negativity

During this time period, Interaction between visual noise and distance showed a significant effect (noise x distance; $F\ (4,44) = 6.02$, $P < 0.05$). There was no main effect of quantity (distance) on no-noise numbers ($F < 1$), whereas there was a main effect of visual quality ($F\ (2,22) = 9.34$, $P < 0.05$). A significant distance effect was observed for medium and dense noise added numbers ($F\ (2,22) = 6.34$, $P < 0.05$ for medium noise x distance and $F\ (2,22) = 7.43$, $P < 0.05$ for dense noise x distance). There was no significant main effect of noise during this period ($F < 1$).

Second Posterior Positivity

Second posterior positivity was not observed for no noise stimuli, so the analysis was limited to noise added-stimuli (i.e. medium and dense noise). A significant main effect of visual quality revealed within the time period between 150 ms and 175 ms ($F\ (1,11) = 16.39$, $P < 0.05$) as well as quantity ($F\ (2,22) = 7.89$, $P < 0.05$). The interaction between visual quality and quantity also yielded a significant effect ($F\ (2,22) = 6.3$, $P < 0.05$).

Second Posterior Negativity

Second posterior negativity was not observed for no noise stimuli. However, the interactive effect of visual quality and quantity was significant ($F\ (2,22) = 7.4$, $P < 0.05$).

Late Posterior Positivity

A significant effect of visual quality and quantity interaction was not found $(F<1)$. The post hoc analysis suggested that the significant effect was observed for dense noise stimuli. On the other hand, the main effect of visual quality was statistically significant (($F(2,22) = 9.07$, $P < 0.05$) showing that dense noise added stimuli is most difficult to identify. In the same time window, the main effect of quantity was also significant ($F(2,22) = 21.15$, $P < 0.05$)) reporting that far numbers are perceived easier than other distance factors. Separate analysis showed that dense noise and medium noise manipulated numbers differ significantly ($F(1,11) = 14.3$, $P < 0.05$). $F(1,11) = 13.2$, $P < 0.05$, $F(1,11) = 7.06$, $P < 0.05$

The analysis of PC1 suggested that posterior and occipital regions were involved in all cognitive processes during early and late stimuli perception (visual quality and quantity).

PC2

The first significant effect reported was 76 ms after stimulus onset time for noise added stimuli vs. 102 ms after stimulus onset time for noise-added (dense and medium noise added) stimuli. During this 50 ms time window there was no statistically significant visual quality effect determined between medium and dense noise stimuli ($F < 1$), but there was a significant effect determined between no noise and dense noise stimuli ($F(1,11) = 9.07$, $P < 0.05$). This latter effect was suggested to be the latency between responses to noise added stimuli and no noise added stimuli. The significance was around 200 ms following stimulus onset time between close and far stimuli (F (1,11) = 6.7, P < 0.05). However, there was no significant noise effect determined around 200 ms (F < 1). There was a significant interaction between visual quality and distance around 275 ms (F (4,44) = 5.78, P < 0.05). Additional analysis showed that this significance was attributable to the difference between close and far numbers within noise.

PC3

For the no noise added stimuli, the only significant quantity effects were recorded between 100 ms and 150 ms. The first main quantity effect at approximately 100 ms was related to the difference between close and far stimuli (F (1,11) = 8.6, P < 0.05), whereas no significance could be determined between far and medium distance stimuli (F < 1). The effect of close versus far stimuli was observed at around 150 ms (F (1,11) = 7.34, P < 0.05), whereas close and medium stimuli showed no significant effect (F < 1).

For medium noise-added and dense noise added stimuli, statistical significance was reported at around 100 ms, 150 ms and 200 ms. The main quantity effect between the window of 100 and 150 ms was significant (F (2,22) = 11.01, P < 0.05). Post-hoc analysis showed that close and medium distance effects were also significant, as were the close and far distance effects, and the medium and far distance effects. Across the 200 and 300 ms windows, statistical significance was found between close and far distance numbers, whereas medium and far distance numbers were not significantly separable (F < 1).

Visual quality also produced a main effect (F (2,22) = 18.3, $P < 0.05$) for all three visual quality conditions. This effect was interactive with the visual quantity (F (4,44) = 18.3, $P < 0.05$) as it was discussed within noise effects. This finding showed that although visual quality perception started earlier over the occipital regions, it carried over during the first 300 ms period through the central and frontal regions along with quantity perception.

Statistical Analysis of ICA Components

Although PCA and ICA techniques revealed slightly different characteristics, statistical analysis demonstrated similar results for these two techniques.

IC1

First Posterior Positivity

The subsequent main effect was a visual quality and distance interaction around 100 ms following stimulus onset time (F (4,44) = 6.15, $P < 0.05$). The interaction between dense noise and close distance was most significant. The visual quality effect was the most significant variable between no noise and dense noise added stimuli. There was no significant effect between medium and dense noise stimuli ($F < 1$).

First Posterior Negativity

During this time period, there was a significant interactive effect (noise x distance F (4,44) = 12, $P < 0.05$). There was no main effect of quantity (distance) on no-noise added numbers ($F < 1$), whereas there was a main effect of visual quality (F

(2,22) = 8.6, P < 0.05). A significant distance effect was observed for medium and dense noise added numbers (F (2,22) = 5.67, P < 0.05) for medium noise x distance and (F (2,22) = 8.34, P < 0.05) for dense noise x distance. There was no significant effect of noise during this period (F < 1).

Second Posterior Positivity

P2p was not observed for no noise stimuli, so the analysis was limited to noise added-stimuli (i.e. medium and dense noises). There was a significant main effect of visual quality as well as quantity (F (2,22) = 7.89, P < 0.05). Post-hoc analysis showed that the effect was between far and close numbers. The interaction between visual quality and quantity also showed a significant effect (F (2,22) = 6.89, P < 0.05).

Second Posterior Negativity (N2)

N2 was not observed for no noise stimuli. The interactive effect of visual quality and quantity was significant (F (2,22) = 9.73, P < 0.05). For medium noise stimuli, the significance occurred between close and far numbers as well as the dense stimuli (close x far).

Third Posterior Positivity

For this IC component, there was no interactive effect (F < 1) between quality and quantity; however, the visual quality and quantity effects were statistically significant (F (2,22) = 13.1, P < 0.05) for visual quality, and (F (2,22) = 11.6, P < 0.05) for quantity.

IC2

The first significant effect reported for IC2 was 76 ms following stimulus onset time for noise added stimuli, whereas it was 102 ms after the stimulus onset time for no noise added (dense and medium noise added) stimuli. During this 50 ms time window there was no significant visual quality effect between medium and dense noise stimuli ($F < 1$), but there was a significant effect between no noise and dense noise stimuli. This effect was suggested as latency between response to noise added stimuli and no noise stimuli. The subsequent significance was determined around 200 ms following stimulus onset time, between close and far stimuli; however, there was no significant noise effect determined around 200 ms ($F < 1$). There was a significant interaction between visual quality and distance around 275 ms ($F(4,44) = 7.8$, $P < 0.05$). Further analysis showed that this significance was observed according to the difference between close and far numbers within noise factors ($F(1,11) = 6.5$, $P < 0.05$ close x far and ($F < 1$) close x medium for medium noise; $F(1,11) = 7.8$, $P < 0.05$ close x far and ($F < 1$) far x medium for dense noise). It showed that medium distance numbers interchanged the significance between two noise conditions, which shows an influence of visual quality on quantity.

IC3

For no noise stimuli, the only significant quantity effects were recorded around 100 ms and 150 ms. The first main quantity effect around 100 ms was related to the difference between close and far stimuli, whereas there was no significance between far and medium distance stimuli ($F < 1$). The effect of close versus far stimuli was carried around 150 ms, whereas close and medium stimuli showed no significant effect ($F < 1$).

For medium noise added and dense noise added stimuli, significant effects were reported around 100 ms, 150 ms and 200 ms. The main quantity effect between the window of 100 and 150 ms was significant ($F(2,22) = 12.3$, $P < 0.05$). Post-hoc analysis showed that close and medium distance effect was significant along with close and far distance effect, and medium and far distance. The close and far distance number effect was significant over the windows between 200 and 300 ms , whereas the medium and far distance numbers were not significantly separable ($F < 1$) in the same time interval.

The visual quality was also a main effect ($F(2,22) = 23.7$, $P < 0.05$) for all three visual quality conditions. This effect was interactive to the quantity ($F(4,44) = 13.08$, $P < 0.05$) as it was discussed within noise effects. This result showed that although visual quality perception began earlier over the occipital regions, it continued during the first 300 ms period through the central and frontal regions along with quantity perception.

Table II-4 The summary of the PC1 and IC1 statistical analyses

Approx. peak time	PC1	IC1	Latency (ms)
100 (ms)	$p(\text{noise x distance}) < 0.05$	$p(\text{noise x distance}) < 0.05$	N/A
130 (ms)	$p(\text{noise x distance}) < 0.05$	$p(\text{noise x distance}) < 0.05$	N/A
175 (ms)	$p(\{\text{medium, dense}\} \text{ x distance}) < 0.05$	$p(\{\text{medium, dense}\} \text{ x distance}) < 0.05$	N/A
200 (ms)	$p(\{\text{medium, dense}\} \text{ x distance}) < 0.05$	$p(\{\text{medium, dense}\} \text{ x distance}) < 0.05$	20
280 (ms)	$p(\text{noise}) < 0.05$ $p(\text{distance}) < 0.05$	$p(\text{noise}) < 0.05$ $p(\text{distance}) < 0.05$	N/A

Table II-5 Summary of the PC2 and IC2 statistical analyses

Approx. peak time	PC2	IC2	Latency (ms)
100 (ms)	$p(\text{noise}) <0.05$ $p(\text{distance}) <0.05$	$p(\text{noise}) <0.05$$p(\text{distance}) <0.05$	N/A
200 (ms)	$p(\text{noise x distance}) <0.05$	$p(\text{noise x distance}) <0.05$	N/A
275 (ms)	$p(\text{noise x distance}) <0.05$	$p(\text{noise x distance}) <0.05$	N/A

Table II-6 Summary of the PC3 and IC3 statistical analyses

Approx. peak time	PC3	IC3	Latency (ms)
100 (ms)	p(distance) <0.05	p(distance) <0.05	N/A
150 (ms)	p(distance x noise) <0.05	p(distance x noise) <0.05	10
200 (ms)	p(distance) <0.05	p(distance) <0.05	N/A
275 (ms)	p(noise x distance) <0.05	p(noise x distance) <0.05	10

III. DISCUSSION

The aim of the present study was to understand the influence of number quality on the judgment of number quantity along with the underlying brain dynamics of number perception. The two-digit number stimuli were chosen to address this question according to their relative distance from the reference number, 65, and the visual quality of number stimuli were degraded by “salt and pepper noise,” which is typically seen in familiar images (i.e., on a TV screen, computer screen, pictures taken with a dusty objective, CCD faults of digital camera, etc.). This very familiar noise, represented as randomly occurring white and black dots, presents an underlying idea that noise limits the visual perception sensitivity; but it does not block the quantitative perception totally (Pelli and Farell, 1999).

Accordingly, the chapter provides an opportunity to discuss the results in relation to visual quality and the quantity as behavioral results, ERP results along with the PCA and ICA results, respectively. Then, the relationship between behavioral and ERP data is explored. The similarities and contradictions with the related literature are discussed later in this chapter. In the conclusion section, the overall results are summarized. In addition, a subsection addresses the contributions to the literature. The chapter is concluded with possible implications of results, the implication limitations of the study and future studies.

Behavioral Results

Our behavioral results showed a statistically significant main effect of visual quality. The longer RTs were reported for stimuli manipulated by visual noise. The increase in the noise level (i.e., dense noise > medium noise) significantly increased the RTs suggesting that quality and quantity of number stimuli are processed as a whole even if the quality is not a part of the attended stimulus. In other words, the unattended visual noise manipulation influences the evaluation of basic features of the stimulus and affects the ability of subjects to judge the numbers. This quality effect was consistent with that reported in previous stimulus studies (Cohen-Kadosh et al., 2005, 2006, 2007; Foltz et al., 1984; Henik et al., 1982; Tzelgov et al., 1992; Suzcs et al., 2005).

The second main effect observed was quantity (i.e., the distance effect from the reference number, 65). A classical distance effect was identified and studied over the past couple of decades suggesting that the increasing distance between two numbers decreases the RTs (Moyer et al., 1967; McCloskey et al., 1985; Dehaene et al., 1992; McCloskey et al., 1992; Campbell, 1994; Cipolotti et al., 1995; Seron et al., 1997). The number stimuli without visual noise manipulation were processed as the classical distance effect (i.e., the closer the number, the larger the RT becomes as it increases proportional to the distance; Moyer et al., 1967; Hinrichs et al., 1981; see Figures II-4,5, and 6). However, the distance effect between medium and far distance stimuli is not significant in comparison to close distance stimuli and increased in the dense noise condition (Figures II-5 and 6). Surprisingly, RT for the medium distance number stimuli was shorter than far distance number stimuli for manipulated number stimuli. The latter suggests that the number comparison strategy was changed in reference to the visual presentations of number stimuli.

This result challenges the findings of Dehaene (1996) and Pinel et al. (2001). They suggested that the distance effect is not influenced by the visual presentation of numbers neither for the one-digit nor for two-digit numbers. On the other hand, Cohen-Kadosh et al. (2007) interpreted the luminance effect on number perception as the extension of congruity effects (i.e. comparing smaller size 35 and larger size 67 or larger size 35 and smaller size 67) (Foltz et al., 1984; Henik et al., 1982; Tzelgov et al., 1992; Suzcs et al., 2005). They suggested that the visual presentation of the number stimuli influences the judgment of number quantity. Accordingly, the present study makes a direct assessment of the visual quality judgment on two-digit Arabic numbers.

The second aspect of our two-digit number comparison study was the spatial effect of response side. There was no significant difference between the RTs reported for left and right hand side responses. Therefore, the SNARC effect was found to be compatible with these findings (Dehaene, 1996; Pinel et al., 2001), suggesting that there is no bias of response side (left-hand response for smaller numbers and right-hand response for numbers larger than the reference).

Electrophysiological Results

One limitation of the ERP experiments is that it is very difficult to know which latent ERP component is responsible for the observed changes between different conditions (Handy, 2004). The best strategy for that is analyzing the ERP waveform differences between different conditions and predicting effects (Luck, 1998). In consequence, well-characterized ERP components examined under similar conditions are chosen to interpret our results. However, these components may also be involved in different conditions and can vary from one experiment to the other (Luck, 1998; Handy, 2004).

The ERPs were affected by stimulus representation (visual quality) and by distance (quantity) from the reference number. The quality effect was observed mainly on early P1 and N1 components, and was reflected by differences in perceptual processing of two-digit numbers. The first distance effect was observed on N1 for the no noise stimuli over bilateral posterior regions. The same effect was elicited for noise added stimuli (i.e., medium and dense noise) as P2p components. The distance effect was pronounced on the right hemisphere for medium noise stimuli, whereas it was bilateral for dense noise stimuli (Figure II-9) on the right parietal electrode for medium noise. N2 was bilaterally observed for dense and medium noise added stimuli. The latency and the slope of the transition between two visual quality levels defined the difficulty of the stimuli (Figure II-7).

The visual quality of noise modulated the quantity. Although the difference between close and far numbers was always significant, the significance value between medium distance and other distance conditions interchanged (i.e., no significant difference between close and medium numbers for medium noise; but significance between close and medium numbers, along with no significance between medium and dense noise; Figures II-4, and 5). Furthermore, we determined that the visual quality caused a proportional latency, and, finally, the distance effect triggered the motor preparation over the central electrodes around 270 ms following the stimulus onset (Cz; Figure II-8). This latter result was interpreted as a distance effect, in which the interaction between quality and quantity ended. The interaction was statistically significant for P1, N1, P2p and N2.

Table III-1 Quality and quantity interactions

Electrodes	T(ms)	No-Medium	No-Dense	Medium-Dense	Description
P1	104-122	*	*		Noise level was not processed yet
N1	140	*	*	*	Interaction for all quality levels
P2p	175			*	Only response was for noise added stimuli
N2	240-280			*	

* indicates the significant differences (latency and amplitude) for $p<0.05$.

Evaluation of Visual Quality

The contrast between stimuli and background was the largest for the no noise stimuli supporting the luminance congruity effect by Cohen-Kadosh et al. (2007). Stimulus quality processing was reported with a larger P1 on the midline and posterior regions (Figures II-7, 8, and 9) for all three visual quality conditions. The quality modulation did not differ between the noise-added stimuli (dense and medium), though it was significantly distinct between noise added and no noise added stimuli. Specifically, P1 was larger for the noise added stimuli. The P1 peak amplitude reported that visually manipulated stimuli requires more attention; however, the attention was limited to discriminate the unattended attributes of background. Namely, the subjects only identified the unattended stimulus attribute as no-noise added and noise-added stimuli. The descending transition through the N1 peak indicated the number judgment for all three quality levels (Dehaene, 1996).

The stimulus quality also impacted the N1 amplitude and latency features. The N1 was bilateral (i.e., both hemispheres were active) for all three levels of visual quality. The amplitude value of N1 represents the stimuli difficulty, whereby the higher the negativity value, the easier the number processing became (Dehaene, 1996). This observation was confirmed by Turconi et al. (2004), as both N1 latency and topography were affected by stimulus presentation (letter or numbers) as the first bilateral posterior negativity. In addition, Pinel et al. (2001) and Turconi et al. (2004) suggested that the right hemisphere is involved in the identification and processing of Arabic numbers, whereas letters induce more left hemispheric activity. To this extent, previous studies suggested that visual manipulation caused a letter processing-like effect showing left hemispheric activity in tandem with that of the right hemisphere.

P2p is a complementary component for noise-added stimuli to identify the level of noise degradation. A similar suggestion could be made for P2p modulation and latency as it was explained for N1. P2p is the largest magnitude component on the left hemisphere for dense noise added stimuli. Therefore, as the noise manipulation increased, the processing may show a perception character similar to the letter perception (Figure II-9).

N2 modulation was similar to N1 modulation, leading to complete the visual discrimination between dense and medium noise added stimuli. The midline electrode sites and the central spatio-temporal (PC2/IC2) map suggested an interaction between visual quality and quantity (Figures II-10, 11, and 12, respectively), which was supported by the statistical analysis and summarized in Table II-3, 4, 5 and 6. The RTs were degraded by noise manipulation whereas the classical distance effect (Moyer et al., 1967) was not observed for medium and far distance numbers.

Evaluation of Quantity

The first distance effect was observed in the counter N1 (posterior negativity (PostN)) time window for no noise stimuli (Cz, Figure II-7), as reported by others (Pinel, 2001; Turconi et al., 2004; Szucs, 2005). The most significant difference in ERPs was found for between close and far numbers starting earlier than the discrimination between the far and medium numbers. Previous ERP studies on number comparison reported a similar early distance effect on the N1 component of bilateral parietal regions (Turconi et al., 2004; Dehaene et al., 1996, Pinel et al., 2001; Cohen-Kadosh et al., 2007; Piazza et al., 2007), with larger negativity on the left hemisphere activity.

Evaluation of Visual Quality and Quantity Together

Previous studies showed that N1 is the ERP component during which the number perception first starts and it shows itself as a deep negative peak (Dehaene, 1996; Pinel et al., 2001; Turconi et al., 2004). The same N1 was reported for both single electrode ERPs and PCA/ICA over the parietal regions. However, the slop between P1 and N1 peaks was changed by the addition of noise. Immediately after N1 peak P2p was observed for noise added stimuli. The amplitude and latency of P2p was interpreted as the visual noise effect on distance judgment. P2p was suggested to reflect the attentional posterior positivity during the second assessment on the visual presentation, meanwhile the number quantity assessment (i.e., mathematical computation) continues. Additionally, the slop between P2p and N2 was reflecting a similar character with the slop between P1 and N1.

PCA and ICA Results

PCA and ICA results described the ERP components more objectively and precisely than did the ERP assessments alone for separated processes (Handy, 2004). One limitation of these techniques is that when two separated processes overlap, they may be captured as a part of a single process even if they occur in different brain areas and represent different brain functions (Handy, 2004). In this particular study, PC2, PC3 captured different brain areas and functions along with IC2 and IC3. Therefore, it was not possible to separate single ERP events for these components. Nevertheless, ICA and PCA are very suitable as an alternative technique for spatial mapping (Murray et al., 2008). The largest PC1 and IC1 components showed similar temporal activities to parietal and occipital ERP components of N1, P1, P2p, and N2. The transition between P2p and N2 was taken into account for task difficulty (Pinel, 2001; Dehaene, 1996). The distance effect was more pronounced for dense noise conditions showing that close numbers are most difficult to compare with the reference number. Surprisingly, medium distance numbers were easier to compare. This suggested that visual quality perception and quantity perception occur as a whole and compete with each other (Cohen-Kadosh et al. 2005, 2006, and 2007; Ganor-Stern et al., 2008; Ganor-Stern et al., 2007; Nuerk et al., 2001; Kaufmann et al., 2005).

Relationship between ERP and RT Results

The ERP results showed good accordance with the RT findings. The visual noise manipulation alters the distance judgment for medium distance stimuli as the maximum magnitude (Figures II-4).

In order to summarize the relationship between RTs and the neural basis of the particular number perception task, the temporal and spatial information provided by PCs and ICs were used. The relationship between RTs and ERPs are more pronounced in the dense noise condition (i.e., largest IC and PC) showing a latency in the window between P2p and N2. This delay can be explained by the increasing RT difference between quantity factors. Surprisingly, the response time for medium distance numbers was shorter than far distance numbers for visually manipulated stimuli. This was also pronounced on the largest and second largest PC and IC components. In the medium noise condition, PC1 and IC1 did not report a significant effect of distance between medium and far distance numbers. The latter is in parallel to RT findings shown in Figure II-6. However, there was a contradiction between the brain dynamics and RTs such that PC and IC components reported a significant distance effect between medium and far distance number stimuli whereas RTs did not show this effect.

Overall, the brain dynamics and RTs for no noise stimuli showed a similar temporal dynamic as reported by Dehaene et al. (1996, 2001) with one-digit and two-digit Arabic numbers. However, the manipulation of visual noise altered these dynamics. Cohen-Kadosh et al. (2005, 2006, and 2007) repeated size congruity tasks (i.e. a smaller size for smaller numbers, a larger size for larger numbers as compared to a reference number), and reported that the size of the stimuli affected the judgment of quantity (i.e., distance). The RTs were shorter for the congruent font size with the quantity (for example, 7 in larger font and 5 in smaller font). Similarly, in the current study, the stimuli were manipulated by salt and pepper noise, which also included such numerosity components as dot densities. The ERP results and the RTs showed that specific functions (such as visual manipulation and distance) affect each other on the same brain area in a mixed quantitative and qualitative manner (Figure II-4 and Figure II-5). This may also address the adaptation effect of background in numerosity indicating that human perception carries the information over time and uses it to compare previous and current images (Durgin, 1995, 2008; Burr et al., 2008). In our study, it is addressed as the black fixation screen with an asterisk in the middle of the screen (see Appendix I and Method section).

Conclusion

The primary aim of this study was to analyze the influence of visual noise and the semantic distance of numbers on the perception of number quantity. We hypothesized that the visual attributes (i.e., numerosity and quality) of the number stimulus alters its neural representation (i.e., quantity). Table III-1 concluded the statistical results of the interaction between visual quality and quantity during the particular two-digit number comparison task. In the current study, well-characterized ERP components were chosen, (Dehaene, 1996; Turconi, 2004; Pinel, 2001).

Two seminal fMRI studies by Cohen-Kadosh et al. (2007) and Piazza et al. (2007) elaborated the relation between the presentation of number stimuli and abstract representation of the number in IPS to determine the extends of such interaction. They reported that parietal lobes of both hemispheres were involved in the number perception. Therefore, the focus herein was on parietal electrodes to advance the studies a step forward.

Hinrichs et al. (1981) reported a logarithmic increase in RTs when the distance between a two-digit number stimulus and the memorized reference number decreases. Later, Dehaene et al. (1990, 1996, and 1997) suggested that processing of numerical distance and visual representation of the stimulus is expected to rely on different cognitive functions. In other words, he suggested an AFM model such that the visual perception of the numbers and quantitative judgment of numbers are sequential and independent. In addition, Dehaene suggested that the logarithmic distance effect on RTs will remain unchanged regardless of the sensory presentation of the number stimuli. Specifically, the semantic processes of number quantity are not affected by the presentation of number stimuli. In this context, the current findings challenge the AFM design. The assessment of the AFM design predicts that number quality and number quantity are two sequentially independent processes and do not overlap in the temporal domain (Dehaene, 1996; Pinel, 2001; Plodowski, 2003). The current study suggests that the visual quality process starts before the quantity judgment; however, these two processes overlap in the temporal domain. This may suggest that mental number perception depends on the success and strategy of sensory visual processing (Hunter, 1957). If the visual processing fails, the number comparison could not be performed.

The overall conclusion of the present study is that ERPs, ICs and PCs along with RTs suggested a strategy of quantitative perception (i.e., number comparison) based on the qualitative attributes of the stimuli highlighting the importance of the design of the task and the methodology. Therefore, if the design and task parameters are changed, the RTs and brain dynamics would slightly change. Nevertheless, the hemispheric differences reported for visually manipulated stimuli provide a better understanding of the underlying mechanism(s). In this context, Ansari (2007) stated that number perception is a complicated process and the experimental design chosen changes the interest of study. Although our task was sufficient to study the influence of visual quality on quantity, the task design is lacked a direct assessment of memory. The cueing studies have shown the involvement of a memory network often suggested as a fundamental component of mental arithmetic which requires understanding of the temporal involvement of the entire process (Szucs, 2005). For example, presenting a random cue of the reference number would help to make an assessment of memory component of ERP around 400 to 500 ms after the stimulus onset (Szucs, 2005; Agam, 2009). Hence the further studies are necessary to understand temporal dynamics of the memory involvement during a two-digit number comparison task.

This study contributes to the literature regarding task design parameters and spatiotemporal ICA and PCA analysis. The classical approach to number judgment studies is to change attributes of the attended stimuli (e.g., Arabic v.s. verbal, line vs. shapes, and size and luminance congruity). However, in this study the number stimuli remained the same (Arabic format) and the background was controlled by visual noise including some quantitative attributes (i.e., dot density). Classical background quantity judgment studies are performed using an adaptation cue. Instead, we simultaneously presented these two parameters and made an assessment that these two parameters overlap in the temporal domain. In addition, classical studies include more than one process but do not use the PCA and ICA approach to make an assessment on temporal ERP components. However, the PCA and ICA approaches did not only provide temporal domain information but also validated the results of each other in the spatiotemporal domain. Essentially, the same brain regions were captured by these two methods; however, PC1 was more sensitive to asymmetries between the two hemispheres.

Possible Implications of the Results

Dyscalculia (D) refers to developmental mathematical disorders which are observed during the initial acquisition of numbers and mathematics whereas acalculia occurs in a later stage of life and caused by neurological injuries such as stroke. Developmental Dyscalculia (DD) is generally described as a disorder in mathematical abilities, presumed to be due to the impairment of non-specific brain function (Kosc, 1974; Shalev, Manor, and Gross-Tsur, 1993; Shalev, Manor, Kerem, Ayali, Badichi and Friedlander, 2001). Mussolin, Mejias and Noel (2009) studied the format effect on single digit number comparison using Arabic numerals, verbal numbers, canonical dots patterns, non-canonical dot patterns, and random stick patterns in DD compared to normal 10- and 11-year old subjects. DD subjects showed a greater numerical distance effect than the controls. This deficit was more significant with two-digit number comparisons (Ashkenazi et al., 2009). However, due to the paucity of DD cases, it has been difficult to draw conclusions regarding number perception in DD subjects.

It may be that visual noise manipulation can model the perception in DD subjects, thus providing a baseline for future studies. Thus, two digit numbers without noise manipulation could be presented to DD patients during a simultaneous behavioral and EEG session. If the brain dynamics and the RTs recorded from DD subjects are similar to the dense noise condition of the current study it would suggest that DD patients perceive the numbers as if manipulated.

Limitations of the Current Study and Future Studies

The current study was limited to only one number comparison task with three visual quality and three quantity factors. Thus, it was not possible to interpret the effects of each factor separately. Future studies should examine the distance effect by changing the reference number from 65 to 50 or 51 as previously reported by Hinrichs et al. (1981). The latter might explain the effects of memorized reference number on the distance judgment. As mentioned above dyscalculia subjects reported difficulties remembering mathematical operations, and numbers. The question can be addressed whether cueing would change the character of number perception. The random cue can include either the reference number or the background for a different experimental condition. In addition, the ERPs over the mid-parietal electrodes could be examined between 400 ms and 600 ms after the stimulus onset time to understand the difference between congruent and incongruent cueing in relation to unattended stimulus parameters (Handy, 2004).

In addition, this study only consisted of one imaging technique, namely EEG. ERPs are used to investigate the timing and organization of specific cognitive processes. Although ERPs provide high temporal resolution, they are limited in aspects of spatial resolution. Combining the ERPs and fMRI can provide temporal and spatial resolution to localize a particular process. For example, fMRI can provide the brain region involved in number comparison whereas the ERPs provide temporal dynamics. This study initially included recordings of combined EEG and fMRI. However, it was not possible to recover enough ERP patterns to generalize the findings. Recently, simultaneous EEG and fMRI recordings are more commonly available; therefore, those simultaneous techniques could advance the fields especially with respect to memory (Handy, 2004).

More in-depth qualitative analysis may also provide a complement to our understanding of cognitive processes. Analyzing the EEG data in the cepstrum domain would provide additional information about temporal and spatiotemporal brain patterns such as absolute and relative power in frequency bands, power ratios between bands, z-score values, and coherence. The cepstrum is a logarithmic transformation of the inverse Fourier transform. It captures information about the rate of change in the frequency spectrum. The signals convolved in time are linearly separable in the ceptrum domain. The ceptstrum domain analyses are widely used to measure seismic activity that resulted from earthquakes, speech, music, and voice recognition. The nature of EEG is very similar to the seismic activities, but surprisingly, cepstrum domain applications in EEG are not very common (Childers et al., 1977). We suggest that linear separation of the EEG signal in the ceptrum domain would provide fine-grained features to increase understanding of the brain dynamics of this particular task. Another improvement of the EEG data processing techniques would be the spatial statistics which provides more sensitive spatial relationships of electrodes by using maximum likelihood approaches. In other words, the activities spatially correlated activities could be classified according to common features to reduce fluctuations of EEG activities of neighboring electrodes.

IV. APPENDIX I DESIGNING and TESTING THE TASK PARAMETERS

The aim of this pilot study was to test the validity, efficiency and measurements of the task.

Materials and Methods

Subjects

6 right-handed male subjects between the ages of 18 and 30 participated in this pilot experiment. After positioning the EEG electrode cap on the scalp, the participant was seated in a dimly lit room and responded to test stimuli by pressing one side of a two-sided button box, the left hand side button for numbers smaller than 65, or the right hand side button for larger numbers.

Tools

Number stimuli were presented in a simple and well-known format of Arabic Arial Narrow, font size of 48 and slide size of 256 x 256. As all the participants were familiar with the representation format, it was assumed that there was no attentional format bias among the tested individuals.

A MATLAB toolbox was used to produce two different levels of “salt and pepper noise” which consists of randomly distributed dots. Finally, the task was programmed in e-PRIME, a Visual Basic-based psychological task development interface, due to its flexibility and richness during the programming and data analysis after the experiment.

Procedure of the Pilot Behavioral Task

The task started with an instruction slide, which terminated after 30 s. The subjects were asked to memorize the number 65 as the reference number and then compare the presented numbers with 65. The reference number was never presented during the task and subjects were reminded several times before the task and an instruction slide included a sentence informing the subject that 65 would not be presented. The visual manipulation levels and factor were neither explained nor included in the instruction. As shown in Figure IV-1, the first pilot study began with a fixation cross, followed by a number stimulus displayed until the response button was pressed. Trials were separated by inter-stimulus intervals lasting 3 to 5s into a block of 72 trials (Pinel et al., 2001). The selected numbers and manipulation factors were shown in the Table IV-1.

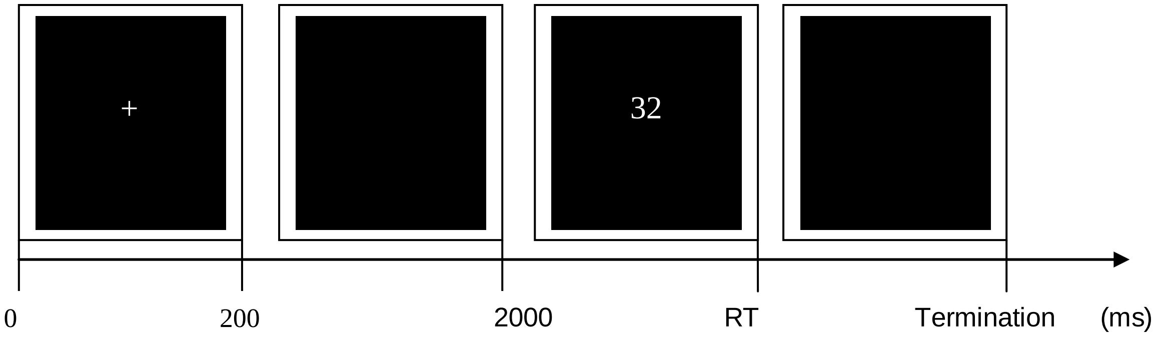


Figure IV-1 A single trial representing the first reaction time task. The trial starts with a fixation cross lasting 200 ms followed by a blank screen shown for 2000 ms. The stimulus disappears as soon as the response (i.e., RT) is provided. The termination of an interstimulus interval was calculated as 800 ms-RT<Termination<2800ms-RT.

Table IV-1 The number stimuli chosen among the numbers between 31 and 99.

Distance	< 65	> 65	Conditions	Noise Conditions
Close	64-63-62-61	69-68-67-66	smaller, larger	no, medium, dense
Medium	51-52-54-56	78-77-76-74	smaller, larger	no, medium, dense
Far	32-38-41-48	98-92-90-82	smaller, larger	no, medium, dense

Preliminary Results and Comments

Results I

The reaction time (in ms) and errors are shown in Tables IV-2 and 3. Fixation cross and blank slides were used among stimuli.

Table IV-2 Behavioral results of the first pilot task. RTs were measured in milliseconds.

	Participant						
Visual Quality	**1**	**2**	**3**	**4**	**5**	**6**	Average
	Close	Close	Close	Close	Close	Close	
No-Noise	364	182	190	566	253	95	275
Medium	444	323	203	326	259	235	298
Dense	397	263	454	399	602	322	406
	1	2	3	4	5	6	
	Medium	Medium	Medium	Medium	Medium	Medium	
No-Noise	430	144	141	639	332	121	301
Medium	434	202	193	572	192	148	258
Dense	607	512	252	698	319	245	439
	1	2	3	4	5	6	
	Far	Far	Far	Far	Far	Far	
No-Noise	202	237	150	493	217	113	235
Medium	431	374	144	461	281	234	321
Dense	503	429	132	258	358	342	337

Table IV-3 Error rate.

Participant	**Error Rate**
1	8.3%
2	5.5%
3	5.5%
4	11%
5	4.2%
6	8.3%
Average	7.1%

Comment I

The first behavioral task consisted of only one block (included 72 trials) to test the fixation parameter. The RTs and the participant’s feedback suggested that using a fixation cross was confusing. Participants reported a tendency toward adding the number stimuli rather than simply using the fixation cross to maintain gaze. The participants also reported that the blank rest period caused them to lose the center of the stimulus screen. Therefore, the task was modified to exclude the blank slides and exchange the fixation cross for a fixation asterisk. The modified test was presented to the same six subjects.

Results II

The error rate of the task without blank slides and with the fixation asterisks was reported as in Table IV-4. The error rate was counted individually for each participant. The individual rate of errors varied from participant to participant.

Table IV-4 Errors for stimuli with fixation asterisk.

Participant	**Error Rate**
1	8.3%
2	5.5%
3	2.8%
4	2.8%
5	7.%
6	5.5%
Average (both pilot participants)	**5.5%**
Average (second pilot participants)	**5.1%**
Average	**5.3%**

Comment II

The task accuracy was increased in the modified design after removing blank slides and exchanging fixation crosses to the asterisks. However, the participants' feedback suggested that the task, consisted of 72 trials of a block, was too short to evaluate the unattended visual manipulation and to compare the number stimuli with the memorized reference number 65. Therefore, the final task was designed to consist of six blocks. Each block had 72 trials and between two blocks with a 30 s rest interval.

In addition to the RTs, the average rate of correct responses for each noise condition (i.e. dense, medium noise added, and, no-noise) was calculated to be 78%, 82%, and 97%, respectively. The RTs were similar for dense and medium noise factors. Therefore, the noise levels were changed for the final experiments to 0%, 60%, 75% of noise density factors were chosen as no-noise, medium-noise and dense-noise, respectively.

Final Task Design

The final task consisted of a short practice block with instructions, followed by six blocks. In the beginning of the task, a short instruction slide appeared for 30 s, then a practice block with 4 stimuli ran for 15 s, followed by six blocks each with 72 stimuli with random inter-stimulus interval (ISI) time between 3 and 5 s and stimulus duration (SD) terminated by an answer given by the participant for at most 2 s. After each block of 288 s, there was a 30 s break to prevent fatigue. Figure IV- 2 illustrates the temporal presentation of the stimuli; high peaks of the steps represent the stimulus and the lines were fixation period between two stimuli.

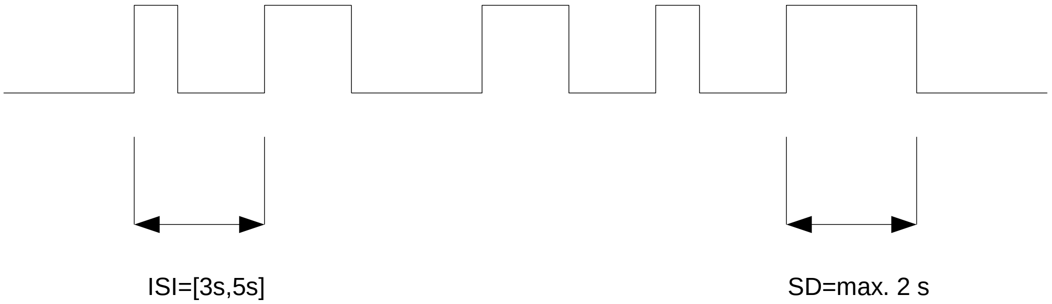


Figure IV-2 Final task design. Inter-stimulus intervals started as fixation asterisks (shown as the high peaks) followed by the stimulus, which was set to disappear as soon as the button press signal was received. The stimulus duration was selected at a maximum of 2000 ms. and it automatically disappeared if there was no response within this period.

Results and Discussion of Pilot Study

Behavioral Results and Discussion

Figure IV-3 illustrates the average block-wise RTs of distance and visual noise factors measured during EEG. The mean RTs for each participant across conditions (noise and distance levels) are shown in Table IV-5. Two subjects were excluded from the pilot analysis because of EEG artifacts. The RT results of six pilot subjects are shown in the Figure IV-3.Repeated measure analysis of variance (ANOVA) was chosen to analyze the statistical significance of the variables, at a P value of 0.05 ($P < 0.05$) because the task design included within and between subject variables as noise and distance factors. As it is shown in figure IV-3, a significant distance effect was reported between far and close numbers ($F(1,5) = 34.2$, $P < 0.05$), whereas there was no significant distance effect between far and medium distance numbers ($F<1$). The main effect of noise was significant ($F(2,10) = 23.5$, $P < 0.05$).

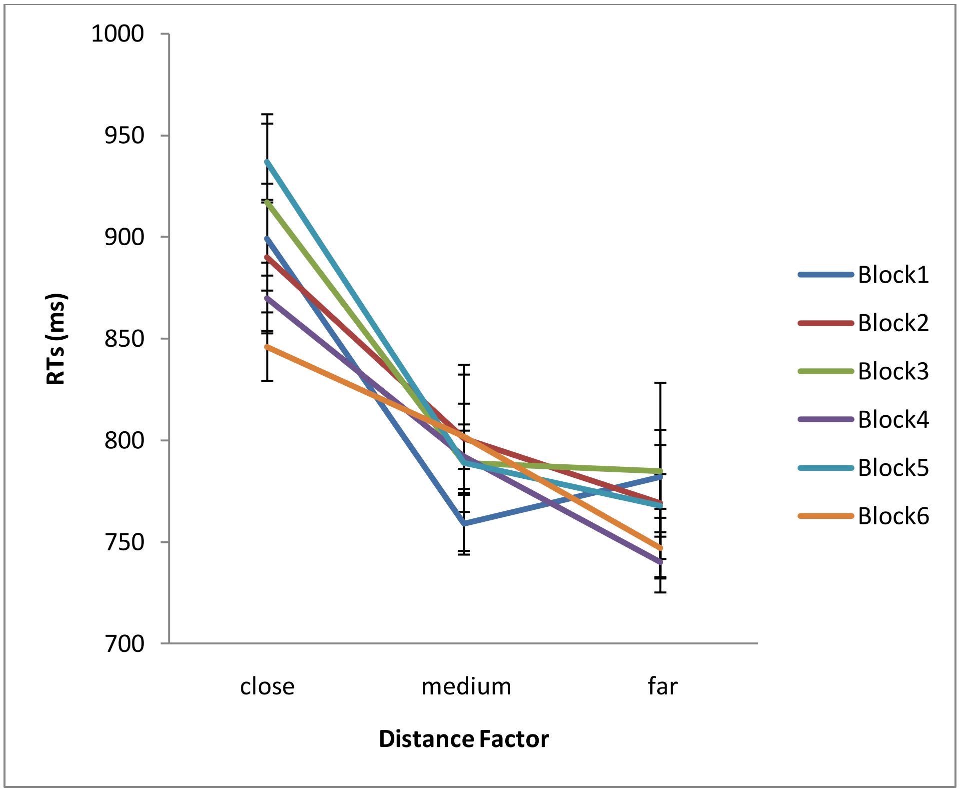


Figure IV-3 Block-wise distance effect on RT (in ms). The mean RTs were calculated for each block for six pilot participants. The mean RTs for close distance numbers were longest for each block whereas the RTs did not show a consistent trend for medium and far distances (i.e. the RT for first block is fastest for medium; the RT of last block was fastest for far distance). The latter indicated an interaction between distance and visual quality.

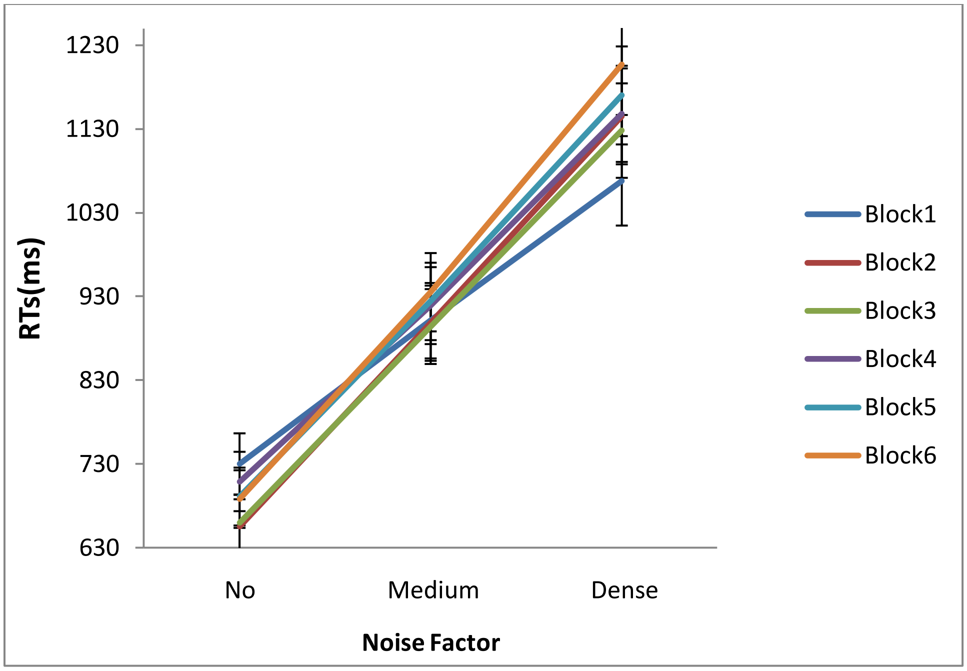


Figure IV-4 Block-wise noise effect on the RT (in ms). The RTs showed similar trends for all blocks. The fastest mean RTs were recorded for no-noise added stimuli whereas the longest RTs recorded for dense noise added stimuli.

The block-wise analysis was employed to develop a final task consisting of sufficient trial numbers to provide a sufficient sample size for statistical analysis. In addition, it was important to avoid too long of a task to provide consistent RTs over the trials. The noise effect did not vary significantly between the blocks as much as the distance effect shown in Figure IV-4. The omitted answers and errors were observed more frequently in the first and the last blocks (Table IV-5). The rate of omitted answers was very low. In other words, participants responded to almost all stimuli in the allowed time duration (before the termination of the trial).

Table IV-5 Mean omitted answers for each block (%).

Block	**Distance**	**No**	**Middle**	**Dense**
1	Close	0.45	0.88	1.00
	Medium	0.97	1.00	0.95
	Far	0.82	0.96	1.00
2	Close	0.95	0.92	0.95
	Medium	0.97	0.96	1.00
	Far	0.77	1.00	1.00
3	Close	0.68	0.95	0.89
	Medium	1.00	1.00	0.82
	Far	0.79	1.00	0.96
4	Close	0.55	0.88	1.00
	Medium	1.00	0.96	0.96
	Far	0.85	1.00	1.00
5	Close	0.52	0.87	1.00
	Medium	0.93	0.95	0.95
	Far	0.89	1.00	1.00
6	Close	0.44	1.00	1.00
	Medium	0.95	0.95	0.96
	Far	0.88	1.00	1.00

Discussion

There is a rational relationship between noise manipulation and RT that was predicted from the task design. The greater the degree of noise manipulation was, the longer the RTs were recorded. Although, in most cases there is a relationship between RT and distance from the reference number of 65, some participants responded faster to the medium distance numbers than to the far distance numbers, which might answer the question of whether the brain compares the numbers digit by digit or mixes them in a special analog order.

Our block-wise analysis results suggest that the negative peaks represent the end of the learning process. Due to the visual variety of the stimuli, noise manipulations, distance, conditions, and the fact that there were 24 different numbers, the participants had to refresh their memory (re-learning process) three times between measurements. The noise effect was otherwise stable for each block. No-noise and dense noise stimuli produced a negative feedback whereby when the RTs increased for dense noise stimuli, the RTs decreased for no-noise stimuli.

The subjects were less accurate for the first three blocks of the task as shown in Table IV-5. Therefore, three blocks of a practice task was given to the participants before the actual recording.

The overall conclusion was that visual quality (i.e. noise) was durable during all experiments and increased the RTs, as suggested by the quality and quantity interaction.

ERP Results and Discussion

A Brain Vision Analyzer Software Interface was used to analyze the EEG data. First, the data was inspected manually to reduce the occurrence of any artifacts. After manual inspection, low (0.2 Hz, 48 dB/oct) and high (30 Hz, 48 dB/oct) pass filters were used to eliminate all noise and artifacts.

After filtering, the data were segmented globally followed by ocular correction of eye blinks. The artifact rejection algorithm was then run for the second noise elimination step, followed by a stimulus classification algorithm. The baseline correction algorithm adjusted the DC offset values. Finally, the segments were averaged to reduce the lack of information and/or any overlapping information.

Figure V-5 illustrates the noise modulation conducted over the two-digit Arabic numbers. As suggested in the literature (Turconi et al., 2004; Pinel et al., 2001; Dehaene, 1996), the number comparison effect was reported over the occipital and parietal electrodes (i.e., O1/O2, PO9/PO10) along with their frontal counter-part electrodes (i.e. Fp1/Fp2).

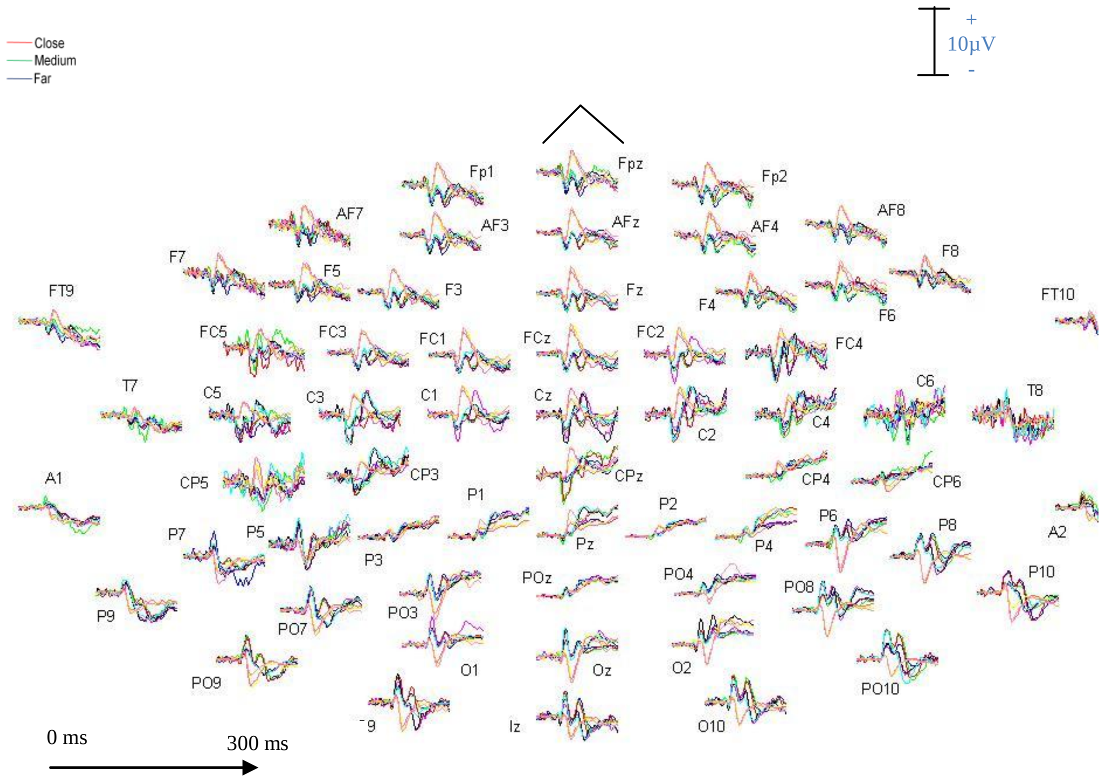


Figure IV-5 The topographical representations of temporal ERPs of the pilot study participants. The vertical axis is the amplitude value in microvolt and horizontal axis is time in ms (50 ms before and 300 ms after the stimulus onset).

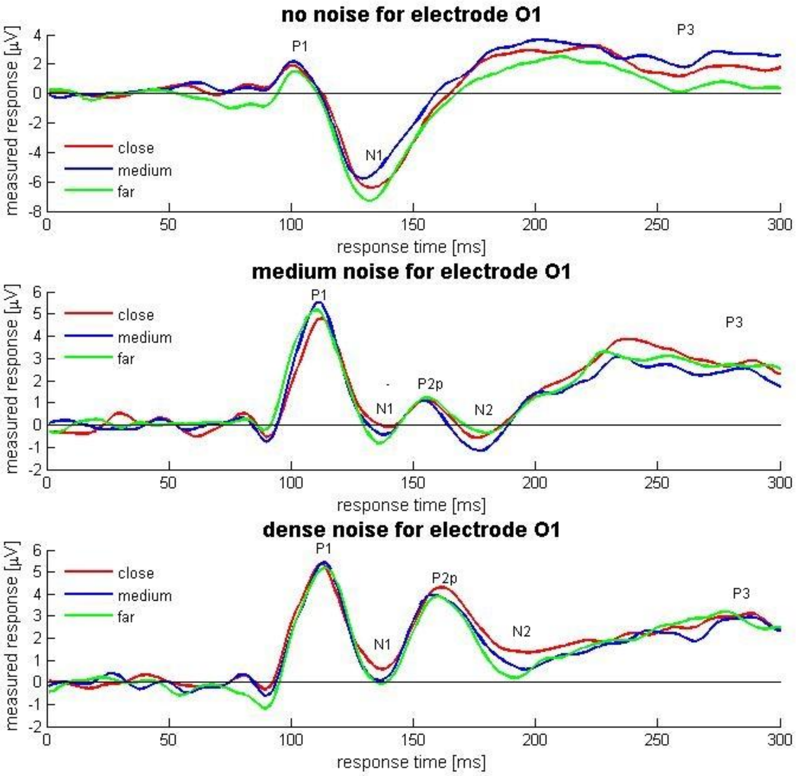


Figure IV-6 The ERP components over the occipital and parietal lobes. An occipital electrode, O1, was chosen to show the occipital brain activities during the task.

The preliminary results of the project validated the model and design parameters. The visual noise (numerosity), distance modulation and their interaction were consistent for four pilot data. Moreover, P1, N1, P2p, N2 were reported as in Figure IV- 6 for the particular number processing task. These ERP components will be discussed for the final project to understand the temporal dynamics and underlying mechanisms of particular number comparison tasks. P1 is the earliest positive peak, suggesting an attentional brain activity and luminance discrimination. P1 magnitude values of noise added stimuli were not significantly different ($P > 0.05$), whereas P1 for no-noise stimuli was significantly lower than others ($P < 0.05$). P2p occurred only for the noise added stimuli. A deep negative peak was reported as N1 for the no-noise stimuli. The N1 window was not large for the noise added stimuli. N2 was negativity recorded after P2p for the noise added stimuli. The motor preparation components of ERP followed N1 for the no noise stimuli, whereas it followed N2 for the noise added-stimuli.

Conclusion

The present chapter included the task development phase and testing, as well as the recording system. It was determined that the fixation asterisk provided a better of fixation for the participants on the stimulus screen. The visual quality level and the noise type were defined in this chapter. A very common visual noise type known as “salt and pepper noise” was used to manipulate the number stimulus. The three levels of visual quality were chosen according to the participants’ reports and the RTs as being 0% for no-noise, 60% for medium and 75% for dense noise stimuli. It was reported that different spatio-temporal patterns over the parietal lobes represented the visual quality, quantity and their influential relationship. Therefore, we decided to discuss this in terms of the parietal, occipital along with posterior central electrodes.

V. APPENDIX III SUPPLEMENTARY ERPs and ICs

Midline Electrodes

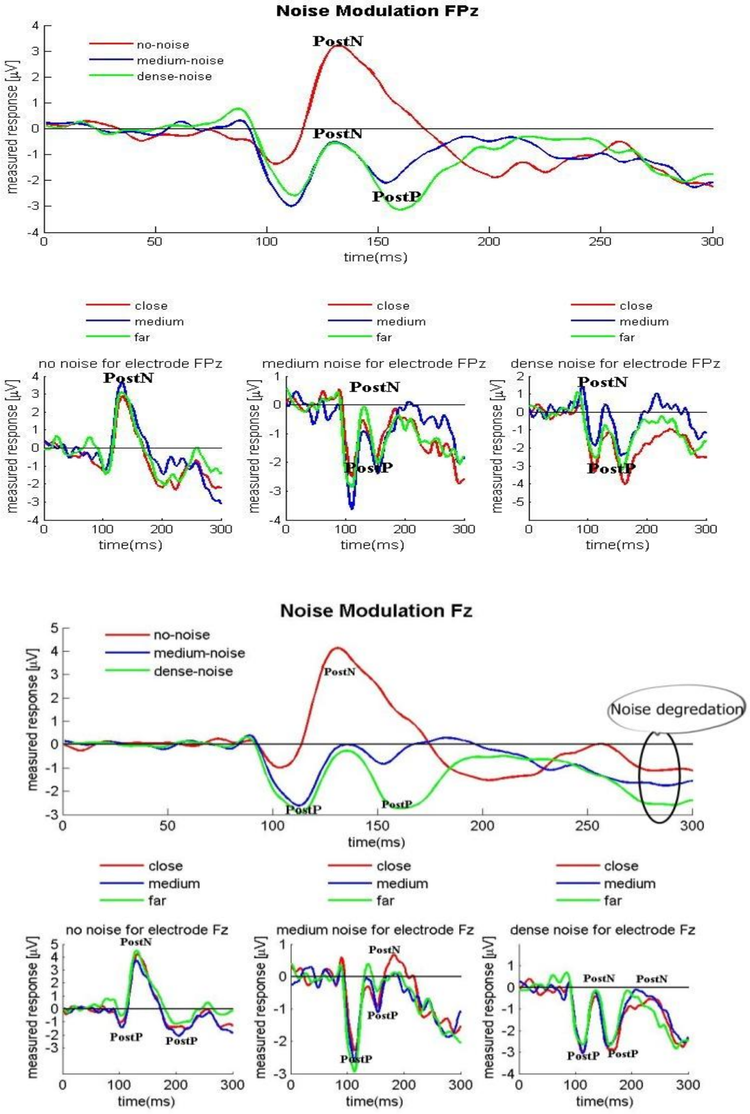


Figure V-1 Frontal midline electrodes. Upper figures show the noise modulation whereas lower figures show distance modulation.

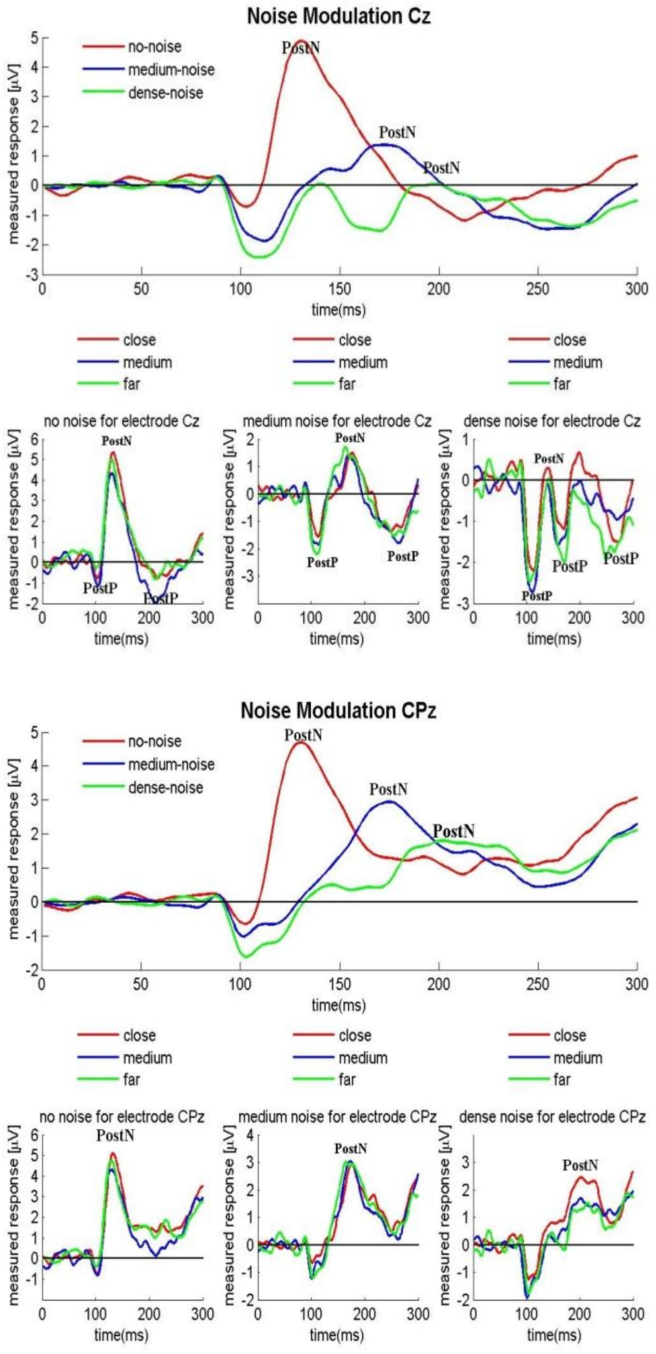


Figure V-2 Central midline electrodes. Upper figures show the noise modulation whereas lower figures show distance modulation.

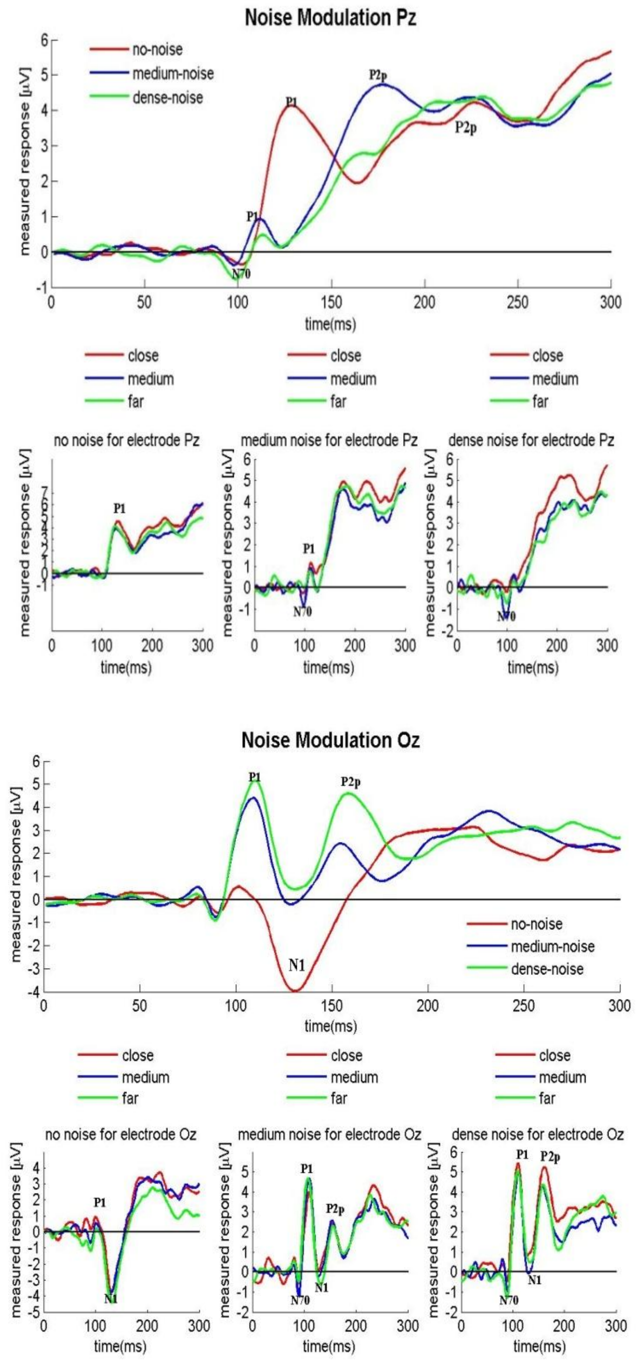


Figure V-3 Posterior midline electrodes. Upper figures show the noise modulation whereas lower figures show distance modulation.

Some Occipital and Posterior ERPs

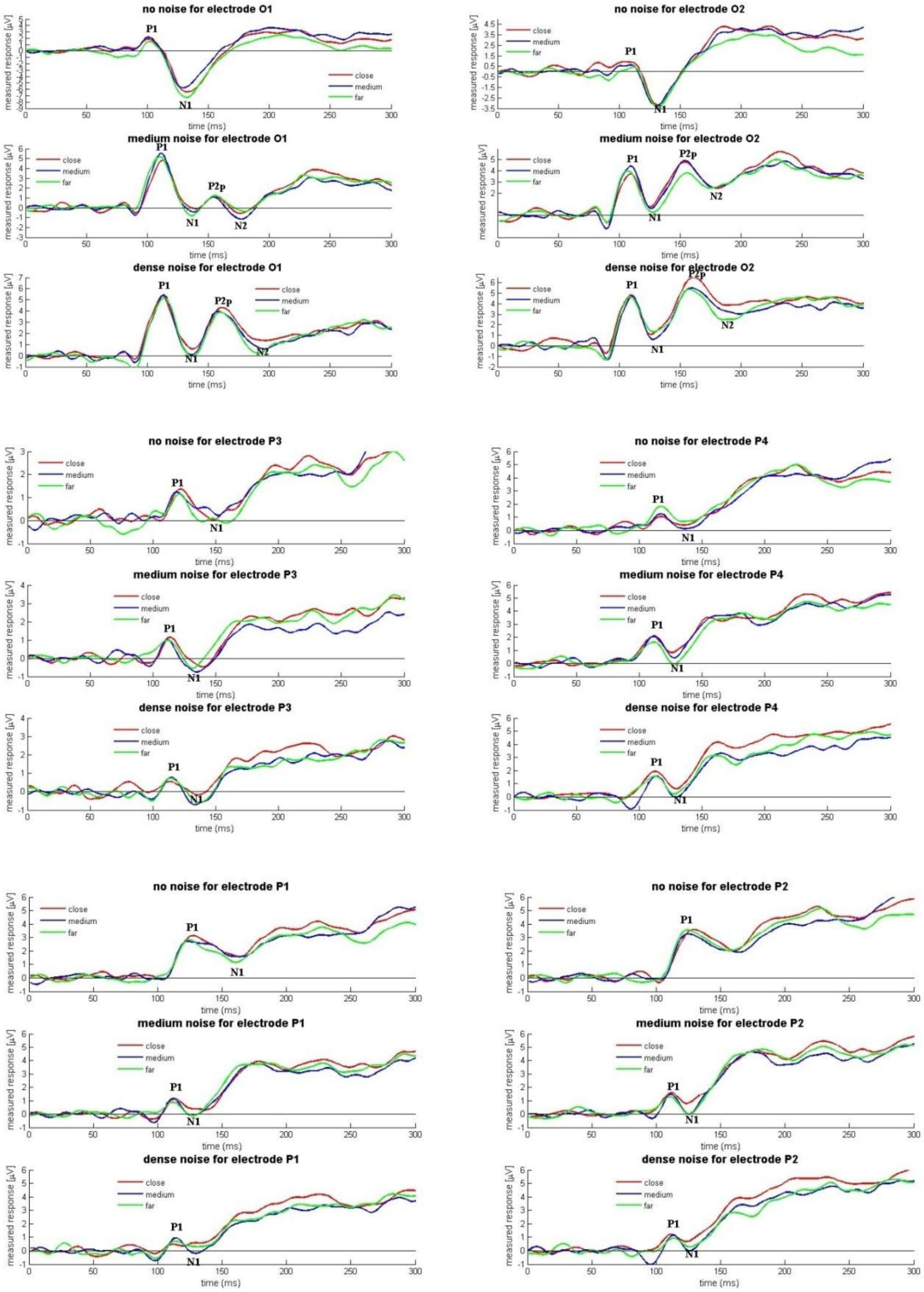


Figure V-4 Supplementary posterior and occipital electrodes

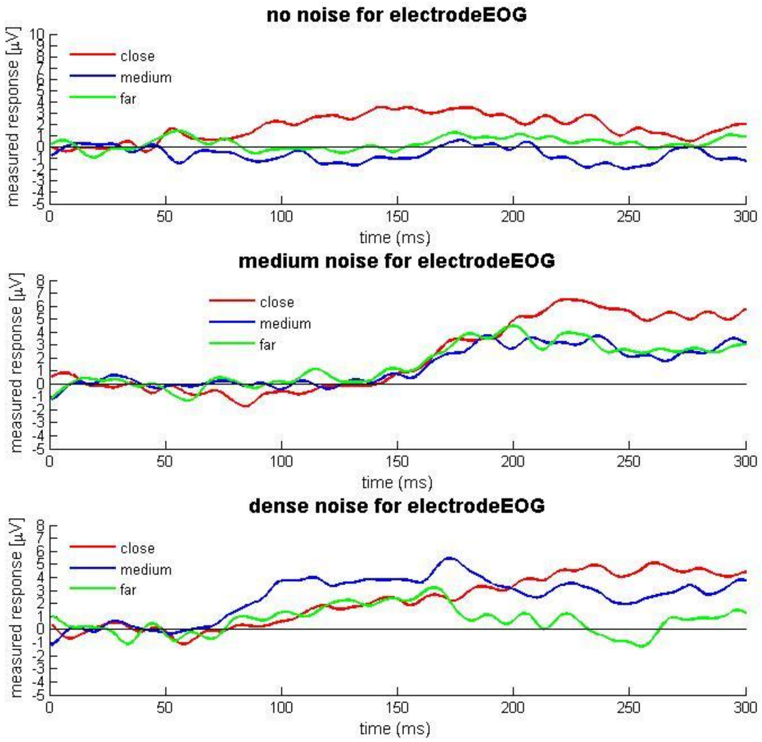
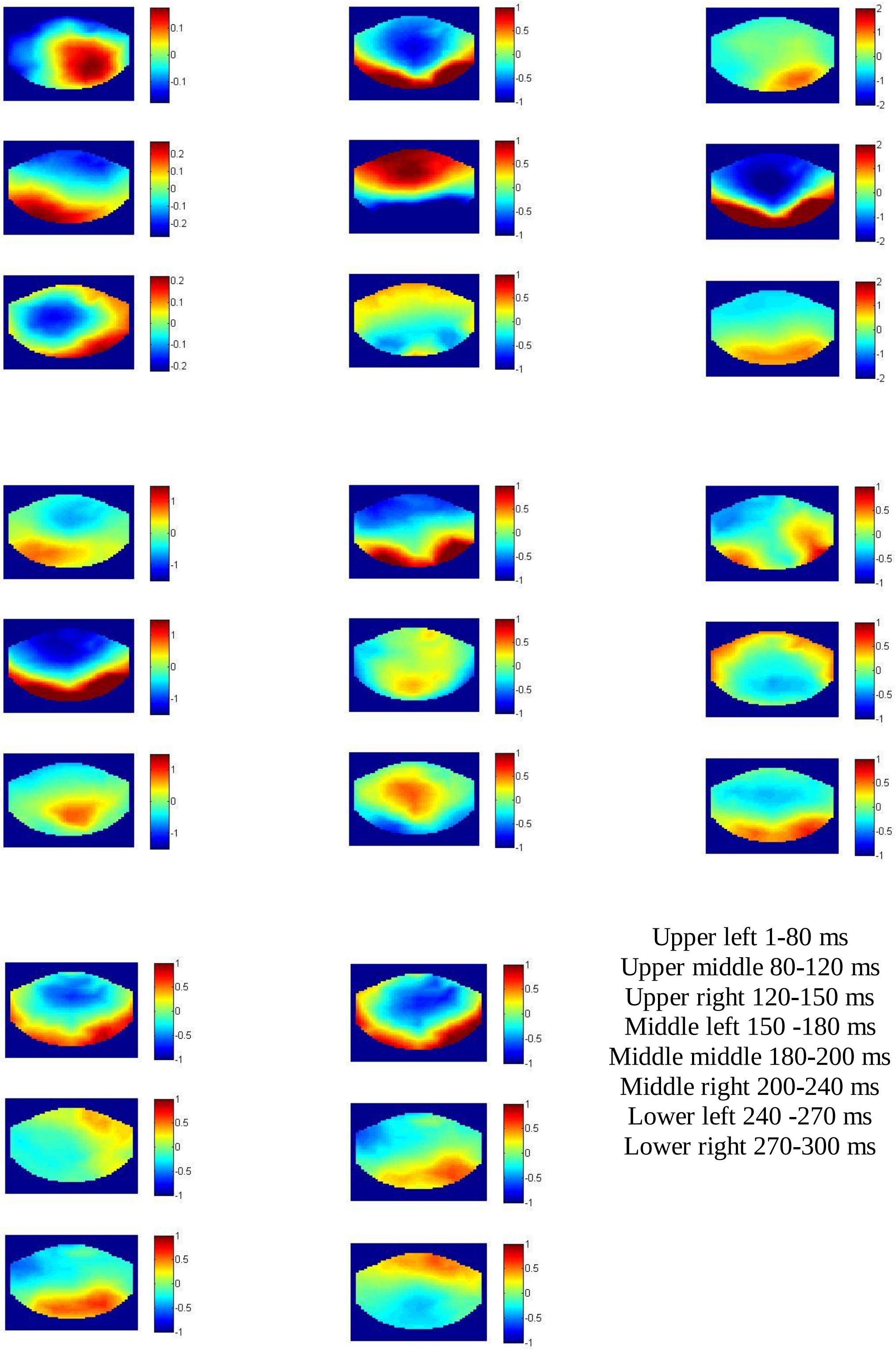


Figure V-5 Eye movement activity. Recorded EOG signals were monitored to detect eye movements that would present eye movement artifacts in the EEG signals.

IC Components



Upper left 1-80 ms
Upper middle 80-120 ms
Upper right 120-150 ms
Middle left 150 -180 ms
Middle middle 180-200 ms
Middle right 200-240 ms
Lower left 240 -270 ms
Lower right 270-300 ms

Figure V-6 Three IC components in shorter windows centering the ERP peaks

BIBLOGRAPHY

Agam, Y., Hyun, J. S., Danker, J. F., Zhou, F., Kahana, M. J., & Sekuler, R. (2009). Early neural signatures of visual short-term memory. *Neuroimage, 44*(2), 531-536.

Allen, P. J., Josephs, O., & Turner, R. (2000). A method for removing imaging artifact from continuous EEG recorded during functional MRI. *Neuroimage, 12*(2), 230-239.

Andrew, E. R. (1992). Nuclear magnetic resonance and the brain. *Brain Topogr, 5*(2), 129-133.

Ansari, D. (2007). Does the parietal cortex distinguish between "10," "ten," and ten dots? *Neuron, 53*(2), 165-167.

Ansari,D.& Karmiloff-Smith, A. (2002). Atypical trajectories of number development: a neuroconstructivist perspective. *Trends in Cognitive Science*, 6, 511-516.

Ashkenazi, S., Rubinsten, O., & Henik, A. (2009). Attention, automaticity, and developmental dyscalculia. *Neuropsychology, 23*(4), 535-540.

Bandettini, P. A., & Cox, R. W. (2000). Event-related fMRI contrast when using constant interstimulus interval: Theory and experiment. *Magnetic Resonance in Medicine, 43*(4), 540-548.

Banks, W. P., & Flora, J. (1977). Semantic and perceptual processes in symbolic comparisons. *Journal of Experimental Psychology-Human Perception and Performance, 3*(2), 278-290.

Birn, R. M., Cox, R. W., & Bandettini, P. A. (2000). Detection versus estimation in event related fMRI: Choosing the optimal stimulus timing. *Neuroimage, 15*, 252-264.

Burr, D., & Ross, J. (2008). A visual sense of number. *Current Biology, 18*(6), 425-428.

Burr, D., & Ross, J. (2008). Response: Visual number. *Current Biology, 18*(18), R857-R858.

Campbell, J. I. D. (1994). Architectures for numerical cognition. *Cognition, 53*(1), 1-44.

Carlomagno, S., Iavarone, A., Nolfe, G., Bourene, G., Martin, C., & Deloche, G. (1999). Dyscalculia in the early stages of Alzheimer's disease. *Acta Neurol Scand, 99*(3), 166-174.

Cipolotti, L., & Warrington, E. K. (1995). Towards a unitary account of access dysphasia: a single case study. *Memory, 3*(3-4), 309-332.

Childers, D., Skinner, D., & R. Kemerait (1977). The cepstrum: A guide to processing. *Proceedings of the IEEE*, 65(10), 1428–1443.

Cohen Kadosh, R., Cohen Kadosh, K., Kaas, A., Henik, A., & Goebel, R. (2007). Notation-dependent and -independent representations of numbers in the parietal lobes. *Neuron, 53*(2), 307-314.

Cohen Kadosh, R., & Henik, A. (2006). A common representation for semantic and physical properties: a cognitive-anatomical approach. *Exp Psychol, 53*(2), 87-94.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., van de Ven, V., et al. (2005). Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia, 43*(9), 1238-1248.

Dehaene, S. (1996). The organization of brain activations in number comparison: Event-related potentials and the additive-factors method. *Journal of Cognitive Neuroscience, 8*(1), 47-68.

Dehaene, S. (1997). *The number sense : how the mind creates mathematics*. New York: Oxford University Press.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. *J Exp Psychol Learn Mem Cogn, 21*(2), 314-326.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *J Exp Psychol Hum Percept Perform, 16*(3), 626-641.

Dehaene, S., & Mehler, J. (1992). Cross-linguistic regularities in the frequency of number words. *Cognition, 43*(1), 1-29.

Durgin, F. H. (1995). Texture density adaptation and the perceived numerosity and distribution of texture. *Journal of Experimental Psychology-Human Perception and Performance, 21*(1), 149-169.

Durgin, F. H. (2008). Texture density adaptation and visual number revisited. *Current Biology, 18*(18), R855-R856.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15*(1), 47-56.

Foltz, G. S., Poltrock, S. E., & Potts, G. R. (1984). Mental comparison of size and magnitude - size congruity effects. *Journal of Experimental Psychology-Learning Memory and Cognition, 10*(3), 442-453.

Friston, K. J., Price, C. J., Fletcher, P., Moore, C., Frackowiak, R. S. J., & Dolan, R. J. (1996). The Trouble with cognitive subtraction. *Neuroimage, 4*(2), 97-104.

Fukunaga, K. (1990). *Introduction to statistical pattern recognition (2nd. Ed.).* Elsevier.

Furtuna, J. & Capson, D. (2004). Improved support vector classification using PCA and ICA feature space modification. *Pattern Recognition*, 37, 1117-1129.

Galton, F. (1880). Mental imaginary. *Forthnightly Review*, 28, 312-324.

Galton, F. (1880). Visualized numerals. *Nature*, 21, 252-256.

Ganor-Stern, D., & Tzelgov, J. (2008). Across-notation automatic numerical processing. *Journal of Experimental Psychology-Learning Memory and Cognition, 34*(2), 430-437.

Ganor-Stern, D., Tzelgov, J., & Ellenbogen, R. (2007). Automaticity and two-digit numbers. *Journal of Experimental Psychology-Human Perception and Performance, 33*(2), 483-496.

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55*(4), 468-484.

Godden, D, & Baddeley, A. (1975). Context dependent memory in two natural environments. *British Journal of Psychology, 66(3),* 325-331.

Handy, T. (2004). Event related potentials, *MIT Press*.

Heeger, D. J., & Ress, D. (2002). What does fMRI tell us about neuronal activity? *Nature Reviews Neuroscience, 3*(2), 142-151.

Henik, A., & Tzelgov, J. (1982). Is 3 Greater Than 5 - the relation between physical and semantic size in comparison tasks. *Memory & Cognition, 10*(4), 389-395.

Hinrichs, J. V., Yurko, D. S., & Hu, J. M. (1981). 2-Digit number comparison - Use of place information. *Journal of Experimental Psychology-Human Perception and Performance, 7*(4), 890-901.

Hunter, I. M. L. (1957). Memory: Fact and fallacies. *Penguin*.

Hyvarinen, A., & Oja, E. (2000). Independent component analysis: algorithms and applications. *Neural Netw, 13*(4-5), 411-430.

Hyvarinen, A., & Oja, E. (1997). Fast fixed point algorithm for independent component analysis. *Neural Comp, 9*, 1483-1492.

Hyvarinen, A., Karhunen, J., & Oja, E. (2001). Independent component analysis. *John Wiley and Sons*.

Jiang, Y. H., & Kanwisher, N. (2003). Common neural mechanisms for response selection and perceptual processing. *Journal of Cognitive Neuroscience, 15*(8), 1095-1110.

Jolliffe, I. T. (2002). *Principal component analysis* (2nd ed.). New York: Springer.

Kaufmann, L., Koppelstaetter, F., Delazer, M., Siedentopf, C., Rhomberg, P., Golaszewski, S., et al. (2005). Neural correlates of distance and congruity effects in a numerical Stroop task: an event-related fMRI study. *Neuroimage, 25*(3), 888-898.

Kosc, L. (1974). Developmental dyscalculia. *Journal of Learning Disabilities, 7*(3), 164-177.

Kruggel, F., Herrmann, C. S., Wiggins, C. J., and von Cramon, D. Y. (2002). Hemodynamics and Electroencephalographic responses to illusory figures. *Neuroimage, 14*(6), 1327-1336.

Kucian, K., Leoenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. *Behavior and Brain Function*, 2, 31.

Lemieux, L., Krakow, K., Scott, C., Allen, P. J., Haan, H., & Fish, D. R. (1999). Comparison of the localization of inter-ictal epileptiform activity based on spike-triggered functional MRI and 64-channel EEG source reconstruction. *Epilepsia, 40*, 185-185.

Luck, S.J. (1998). Sources of dual task interference. *Psychological Science,* 9,223-227.

Makeig, S., Debener, S., Onton, J., & Delorme, A. (2004). Mining event-related brain dynamics. *Trends in Cognitive Sciences, 8*(5), 204-210.

Malmivuo, J., Suihko, V., & Eskola, H. (1997). Sensitivity distributions of EEG and MEG measurements. *Ieee Transactions on Biomedical Engineering, 44*(3), 196-208.

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia. *Cognition, 44*(1-2), 107-157.

McCloskey, M., Caramazza, A., & Basili, A. (1985). Cognitive mechanisms in number processing and calculation: evidence from dyscalculia. *Brain Cogn*, *4*(2), 171-196.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*(5109), 1519-1520.

Murray, M. M., Brunet, D., & Michel, C. M. (2008). Topographic ERP analyses: a step-by-step tutorial review. *Brain Topogr, 20*(4), 249-264.

Mussolin, C., De Volder, A., Grandin, C., Schlogel, X., Nassogne, M. C., & Noel, M. P. (2010). Neural correlates of symbolic number comparison in developmental dyscalculia. *J Cogn Neurosci, 22*(5), 860-874.

Mussolin, C., Mejias, S., & Noel, M. P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition, 115*(1), 10-25.

Newman, R. (1998). *The dyscalculia sendrome.* Retrieved from www.dyscalculia.org/thesis.html.

Noel, M. P., & Seron, X. (1997). On the existence of intermediate representations in numerical processing. *Journal of Experimental Psychology-Learning Memory and Cognition, 23*(3), 697-720.

Nuerk, H. C., Weger, U., & Willmes, K. (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition, 82*(1), B25-B33.

Pearson, K. (1901). On lines and planes of closest fit to systems of points in space. *Philosophical Magazine, 2*(6), 559-572.

Pelli, D. G., & Farell, B. (1999). Why use noise? *Journal of the Optical Society of America Optics Image Science and Vision, 16*(3), 647-653.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron*, *53*(2), 293-305.

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage, 14*(5), 1013-1026.

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron, 41*(6), 983-993.

Plodowski, A., Swainson, R., Jackson, G. M., Rorden, C., & Jackson, S. R. (2003). Mental representation of number in different numerical forms. *Current Biology, 13*(23), 2045-2050.

Sanders, A. F. (1983). Towards a model of stress and human-performance. *Acta Psychologica, 53*(1), 61-97.

Sanei, S. & Chambers, J. A. (2007). EEG signal processing, *Wiley*.

Sartori, G., & Umilta, C. (2000). The additive factor method in brain imaging. *Brain and Cognition*, *42*(1), 68-71.

Sartori, G., & Umilta, C. (2000). How to avoid the fallacies of cognitive subtraction in brain imaging. *Brain and Language, 74*(2), 191-212.

Shalev, R., Manor, O., Amir, N., & Grosstsur, V. (1993). The acquisition of arithmetic in normal-children - assessment by a cognitive model of Dyscalculia. *Developmental Medicine and Child Neurology, 35*(7), 593-601.Shalev, R. S., Manor, O., Kerem, B., Ayali, M., Badichi, N., Friedlander, Y., et al. (2001). Developmental dyscalculia is a familial learning disability. *Journal of Learning Disabilities, 34*(1), 59-65.

Smith, S. (1985). Background music and context depended memory. *American Journal of Psychology, 98(4),* 591-603.

Smulders, F. (1993). The selectivity of the age effect on information processing. *Amsterdam University*.

Sternberg, S. (2001). Separate modifiability, mental modules, and the use of pure and composite measures to reveal them. *Acta Psychologica, 106*(1-2), 147-246.

Sternberg, S. (2003). Process decomposition from double dissociation of subprocesses. *Cortex, 39*(1), 180-182.

Szucs, D., & Csepe, V. (2005). The effect of numerical distance and stimulus probability on ERP components elicited by numerical incongruencies in mental addition. *Cognitive Brain Research, 22*(2), 289-300.

Thioux, M., Pillon, A., Samson, D., de Partz, M. P., Noel, M. P., & Seron, X. (1998). The isolation of numerals at the semantic level. *Neurocase, 4*(4-5), 371-389.

Turconi, E., Jemel, B., Rossion, B., & Seron, X. (2004). Electrophysiological evidence for differential processing of numerical quantity and order in humans. *Cognitive Brain Research, 21*(1), 22-38.

Tzelgov, J. (1997). Specifying the relations between automaticity and consciousness - A theoretical note. *Consciousness and Cognition, 6*(2-3), 441-451.

Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling stroop effects by manipulating expectations for color words. *Memory & Cognition, 20*(6), 727-735.

Tzelgov, J., Yehene, V., Kotler, L., & Alon, A. (2000). Automatic comparisons of artificial digits never compared: Learning linear ordering relations. *Journal of Experimental Psychology-Learning Memory and Cognition, 26*(1), 103-120.

Wang, L., Kuroiwa, Y., Li, M., Wang, J., & Kamitani, T. (2001). Do P1 and N1 evoked by the ERP task reflect primary visual processing in Parkinson's disease? *Doc Ophthalmol, 102*(2), 83-93.