SQUARC Effect and Contextual Dynamics of Numerical Magnitude

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Perception of the world is rooted in the perception of its continuous and discrete quantitates. All life forms, from smallest to largest, constantly need to adjust to the environment in terms of space, time, speed, light, temperature, and all sorts of quantities. A key component of the evolution is the ability to discriminate, count, and estimate numerosities. Some authors even propose unified processing mechanisms for quantity processing, of which good example is ATOM (A Theory of Magnitude). Non-verbal animals and preverbal infants possess remarkable ability to understand the concept of cardinality, albeit limited only to approximation. The precise extraction of numerical magnitudes and the development of sophisticated number systems can be obtained only through the use of language, however, it still obeys the psychophysical principles like Weber's law, revealed through the presence of numerical distance and size, SNARC, STEARC, and other psychological effects.

This doctoral thesis is about both quantity dimensions. One experiment attempted to obtain evidence for the hypothesized SQUARC effect (Spatial-Quantity Associations of Response Codes) in which smaller quantities are responded faster with left spatial codes, and larger quantities with codes on the right. Three other experiments tested the possible cognitive differences between cardinal and nominal numerical contexts in priming and semantic blocking paradigms. Total number of 65 Japanese students from Kobe university participated in the experiments.

The prediction tested in the SQUARC experiment stated that targets on the left within the visual modality will be detected faster after presentation of auditory cues with low pitch/loudness, and faster on the right if the audio has a high pitch/loudness levels. Although the obtained results were in accordance with the hypothesized pattern, statistical analysis did not reveal

significant effects. Thus, it was concluded that the effect was not obtained in the experiment. The next two experiments were designed to test the processing of Arabic numerals within cardinal and nominal contexts, i.e., to look for hypothesized differences between both. The performance was measured in a primed numerical comparison tasks, and data were collected for calculation of the classical distance effect which was used as a cognitive measure. First experiment asked participants to read prices and postal codes silently or aloud that appeared on the computer screen as primes, and make a button-press for smaller/larger than five targets in a comparison-to-standard task. Evidence for slightly faster performance of cardinal primes over nominal ones was obtained, which was interpreted as an indicator that underlying processes for nominal numerical context may be different from cardinal ones. The third experiment extended the procedure's measuring capabilities up to eight distance units and implemented counterbalanced design, but in contrast to the first experiment, it did not obtain context effects, instead it recorded large deviations from the classical distance effect for primes that were read aloud. The findings were explained in terms of digitalization of the analog mental number line with the help of language. The fourth experiment also dealt with the topic of numerical context, but instead of priming, it used semantic blocking paradigm for its purposes. Typically in this paradigm, pictures and words from different semantic categories are presented in categorically homogeneous and heterogenous blocks and participants are asked to name them. Mostly, blocked pictures are named slower than blocked word, and it is said that this occurs due to semantic competition on a lemma level. For the present purposes, this paradigm was modified to investigate blocked cardinal, neutral, and nominal contexts as well as mixed-context blocks. It was expected for the context to interact with the blocking, but that was not the case. Instead, a main effect for context was obtained and a different type of distance effect was observed, namely the priming distance effect. Again, nominal context was slower than cardinal one. Finally it was concluded that when Arabic digits are named in each context, they automatically activate quantity-related and non-related meanings, of which non-quantitative ones are slower and weaker and quantitative ones are dominant.

Based on the findings in these experiments, final parts of the thesis propose a model for emerging numerical context which hopefully, will contribute for our better understanding of numbers.

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Introduction

It seems that the numbers are older than the universe itself. In fact, the numbers were always there. Although scientists still debate on the issue whether something existed or could exist before the Big Bang, in the context of numbers, the issue is clear-cut. The answer for the existence prior Big Band holds two possibilities: 1 and 0. The value of 1 reveals presence of quantity, regardless of its quality (it may be time, space, mater, etc.) and therefore existence of something. On the other hand, the value of 0 symbolizes an absence of quantity or nonexistence, and this "nothingness" can be adequately described as numerical phenomenon. The question of existence before the universe was born, no matter how paradoxical, reveals the fact that the concept of number is fundamental in this, and other possible universes.

Beautiful as they are, numbers are extremely enigmatic. We encounter them so many times in a day, yet only recently we began to understand their dynamics. Nevertheless, the ability to comprehend, process, and produce numbers is evolutionary gift that we share with the other species. On one hand, even human infants in all their developing business, already possess innate mechanism capable of performing basic arithmetic calculations. Remote and isolated cultures have incredible numerical competences too, but only the linguistic and technologically advanced societies reveal the real potential of numbers. Human necessity to categorize and organize quantitative information led to the invention of Hindu-Arabic numerals. In fact, modern numerals originally come from Indian numerical notations, but after their spread to the West, they became known as *Arabic numerals*. Until it reached its modern logographic form, number concept was expressed by different symbols throughout the centuries and depended on cultural and linguistic advancements (Ifrah, 1985). However, the fundamental property of numerals to convey quantitative information remained constant. Here, it is important to distinguish between the concepts of *number* and *numeral*, where number refers to the general format-free, modality-independent notion of number, whereas numeral implies modality-specific representations (Brysbaert, 2005).

On the other hand, our numerical cognition and comprehension is subject of the natural laws and there are many limitations in our numerical competences. For example, the bigger the number of items we try to comprehend the worse is our performance. In case of numbers, precision and size do not go well hand in hand, and this is reflected in our daily problems to comprehend larger numerals. Luckily, we overcome these limitations with our patient vocal and subvocal counting techniques, stored arithmetic facts, and useful calculation algorithms. However, in the world of numbers, problems do not arise from disorganized systems, quite on the contrary, our mental organization of numerical magnitudes is pretty robust and sometimes it can even cause behavioral biases when there is no particular reason for that.

Most of all, people who have numerical difficulties following a brain injury or disease show us the real importance of the numerical understanding and manipulation. For these people, the questions like "how many?" are even harder than the theory of relativity is to an average teenager. Unquestionably, the role and function of numbers is tremendously important, and numbers are the ones that really spin the world forward into progress. This thesis will touch each of the aspects mentioned above. It will also try to contribute to our collective knowledge on numbers and their intriguing quantitative properties.

1.1 The origins of numerical competence

Biologically, numbers and their magnitudes are tightly related to the survival of animals. Mobile organisms, no matter how primitive they are, have to solve the immediate environmental problems of how many, how much, what size, how long, when, how fast, and so on. Thus, the ability to understand, manipulate and predict quantitative information in the environment is of outmost importance. This ability could be easily one of the fundamental determinants of the evolutionary advancement of organisms in question. The numbers are highly ecologically valid in terms of Darwinian selection, predation, foraging, mating and other occurrences related to survival.

The quantitative information comes in two forms: *discrete* and *continuous*. Modern use of the term *number* mostly refers to the discrete quantity it represents. When people talk about numbers, most of the time they mean sets of discrete units or a quantity that can be obtained by the question of *how many*. However, both quantity forms are interlinked and often transformed from one to another. After all, the discrete quantity can be defined as selected point in the line of continuous quantity. Thus, although the phrase "numerical competence" generally denotes understanding of discrete quantities, it is also suitable for understanding of the continuous quantities.

For a long time, researchers met with skepticism the emerging reports on the numerical competence in animals. Strong reason for this disbelief was the absence of language in animals. Contrary to the nonverbal animals, humans express numbers and other numerical concepts through the use of symbols for quantification. However, one of the critical questions is whether language is really necessary for the numerical competence. Several studies addressed this question in innumerate native Amazonian Indians from Brazil. They came to conclusion that the numerical representation is independent from the language and it is shared with nonverbal animals (Gelman & Gallistel, 2004). Understandably, the numerical competence of Amazonian Indians is basic and therefore limited in precision and arithmetical computation, but certainly its origin is nonverbal.

Undoubtedly, it is a big challenge to understand how animals and humans extract, represent, and process both forms of quantitative information. Nevertheless, in the last 50 years of research on numerical cognition, new evidence is piling up in favor of the related underlying mechanisms. It is now evident that nonverbal animals and preverbal infants posses limited, but remarkable "number sense" (Dehaene, 2011).

1.1.1 Ecological validity of numbers

The numerical competence is essential in the context of natural selection. The reasons could be parasitic, foraging, sexual, predatory, social, etc. For example, numerical discrimination is extremely important for the parasitic brown-headed cowbirds and their victims. The cowbird's selection of the victim's nest primarily depends on the number of eggs already present within the host's nest (White, Ho, de los Santos, & Godoy, 2007). More often, female cowbirds approach and examine nests with eggs and avoid nests without eggs, and they prefer nests with three eggs to nests containing only one egg. Additionally, they prefer nests with eggs smaller or about equal size to their own. This important detail indicates that female cowbirds can discriminate each egg individually according to its size.

Furthermore, the ability to extract quantitative information is crucial for selection of food sources, food-foraging and food-hoarding activities. Between two food cache sites, New Zealand robins often select the larger one, even when the food is cached sequentially at the sites, which disables these birds to compare the quantities at the same time (Hunt, Low, & Burns, 2008). The robin's abilities suggest comprehension of the quantities. They have to remember the amount of food in the first and second caches, to compare both amounts mentally and to make numerical judgment of which one contains more food.

When predators like cheetah hunt for prey, they have to posses general estimate of the herd size they attack. In one study, four cheetah groups from Nairobi National Park in Kenya showed better hunting success in prey herds of 30 or less (Eaton, 1970). The never-ending arms race between preys and predators constantly tweaks the numerical balance between the hunting and hunted groups. Therefore, the numerical discrimination is vital part of the predation and antipredation strategies.

Social interactions between different individuals or groups emphasize the importance of numbers even more. When 21 different lion prides from Serengeti National Park in Tanzania were exposed to playback audio of a single female lion roar, or three individual roars grouped together, they were less likely to approach and attack the three imaginary intruders (McComb, Packer, & Pusey, 1994).

In their natural setting, primates too show numerical competence when they estimate number of individuals within a group, and number of individuals between the interacting groups. For instance, when chimpanzees were exposed to audio playback of hooting and panting sounds that sounded like another rival group, the level of aggression and lethal attacks rose if the two rival groups differed numerically from each other (M. L. Wilson, Hauser, & Wrangham, 2001). The numerical assessment has direct influence on the behavior of these animals, and if the listening group was consisted of three or more male chimpanzees, they were more likely to approach the playback source.

The animal life in the natural wild environment greatly depends on the numerical competence and it is a prerequisite for successful survival. Without this ability, animals cannot optimize their behavior in relation to food sources, competing individuals or groups, predators and preys and therefore, are less likely to survive. Also, animals' numerical abilities can be expanded further by learning and practice in laboratory settings. Through careful design of controlled experiments, researchers in animal cognition and behavior have shown that animals can solve more complex numerical tasks.

1.1.2 Numerical competence in animals, infants, and unschooled young and adults

Although animals are devoid of verbal language, they are able to represent and manipulate numerical information. One of the first rigorous scientific efforts was the one of Otto Koehler. In the year 1951, Koehler was testing the ability of several bird species to assess numbers (Koehler, 1951). He trained parrots, jackdaws, and other birds to match number of items on drawings with varying sizes and arrangements. After seeing a drawing with the indicated number for the trial, the birds had to choose between two different drawings placed on the lids of two food-containing boxes. When birds correctly matched the indicated number of items and the number on the drawings, they gained access to the food reward inside the box. Though Koehler's birds showed incredible capacity to learn small numbers, still they were not able to learn numbers greater than six. Besides, it took very long time and countless trials for the learning to occur.

The extensive numerical training of animals in the experimental designs never occurs naturally. During the training sessions, animals have to be reinforced repeatedly over long periods of time to perform numerical tasks. As a result, there is necessity for evidence of numerical competence and counting abilities obtained in natural settings. For this purpose, Davis and Bradford (1986) simulated natural rat environment where the rats had to find and obtain food from one of the six tunnels. The experimenters controlled the other spatial, olfactory and visual cues, isolating the ordinal position of the tunnels as the only cue rats could utilize to forage. The rats quickly learned to modify their behavior with the change of the ordinal information, even when the spatial configuration of the experimental area changed. Furthermore, the rats were able to remember and discriminate learned ordinal information even after one year and six months. Finally, the experimenters concluded that the numerical ability in rats could be developed in relatively natural settings without tremendous motivational efforts that are often inevitable in artificial experimental designs.

Beside the ability to count discrete quantities, rats are able to discriminate non-numerical, continuous durations as well (Meck & Church, 1983). After their initial training to discriminate two auditory tones with 2-sec duration and eight tones with duration of 8 seconds, they were tested in number and duration discrimination conditions. In the number discrimination condition, number of tones varied in a fixed duration, whereas in the duration discrimination condition, the number of tones was held constant and the duration varied. The rats in the experiment made their response with left and right levers that were inserted in the cage after each presentation of the stimuli, and were rewarded with food if they pressed the left lever for the two tones and shorter durations, and right one for the eight tones and longer durations. It is important to mention that the rats were not cued beforehand for the order of the stimuli. The results were straightforward and rats performed surprisingly well. They could discriminate numbers and durations equally well. Additionally, the experimenters introduced intermediate values in the both conditions. In this case, three tones in the fixed duration condition were responded to with the left lever, while other six tones cued response to the lever on the right. Peculiarly, when rats encountered 4 tones, they were indecisive to press any lever suggesting subjective midpoint in the discrimination.

Lastly, some species can go ever further and surprise with their numerical abilities. Hauser, MacNeilage, and Ware (1996) reported simple arithmetic calculations performed by wild rhesus monkeys. The researchers used the so-called *preferential looking paradigm* and presented possible and impossible events in front of the monkey subjects. An object was placed inside a box and then covered with movable screen, some time delay was added, and when the movable screen was lowered down, the object became visible again. In the possible condition the input was equal to the output. In the impossible condition, two objects were placed inside the box, but only one appeared after the screen removal. The monkey subjects significantly looked longer when they observed an impossible event. Also, they showed prolonged interest for the unusual outcome. This observation suggests rudimentary addition and subtraction abilities in the monkeys.

In the same way, human infants appear to posses innate numerical abilities. An ingenious experiment in the 80s used *habituation-dishabituation protocol* to show that 72 infants (between 16 to 30 weeks old) can discriminate between arrays of two and three dots (Starkey & Cooper, 1980). The experimenters positioned screen on which they presented the arrays of dots in front of an infant. The dots were arranged in lines with identical lengths in order to prevent shape perception (e.g., triangle in the three dots arrays). Each trial started when the infant looked at the array and ended when looked away after habituating to the stimuli. When the number of dots changed on the screen, infants dishabituated and looked longer at the new display. Finally, the authors concluded that infants are at least able to *subitize* (rapid estimation of the number of elements in small sets). Pursuing this further, Strauss and Curtis (1981) replaced the dots arrays with different drawings of familiar objects (e.g., houses, flags, dolls, dogs, parrots, etc.). They kept the number of displayed items fixed, but changed their identity. Results showed that infants (10 to 12 months of age) habituated and dishabituated to the number of items instead of their identity. This study fortified the findings of Starkey and Cooper (1980) by providing convincing evidence for basic numerical competence in infants as young as 16 weeks of age.

Additionally, it was shown that the infants could disregard the modality or the type of the stimuli, and retain only the information about numbers. Thus, infants must posses more general enumerative ability, independent of modality or the type of stimuli used to express numerical information (Starkey, Spelke, & Gelman, 1983). In agreement with the research on animal numerical cognition, preverbal infants are capable of performing simple numerical operations, implying innate structures for the numerical competence. Wynn (1998) reviewed an extensive list of reports on human infants and their numerical competence. Some of them used the *preferential looking paradigm*, including some of her own (Wynn, 1992, 1995). Wynn concluded "infants can enumerate different kinds of entities, and can compute the numerical outcomes of operations over small numbers of entities" (p. 302). Finally she wrote that "findings support the existence of a dedicated mental mechanism specific to number, one which may have evolved through natural selection and which we may share with other warm-blooded vertebrate species" (p. 302).

Preverbal infants and nonverbal animals have innate numerical competence for small sets of objects. This competence is genuine and natural, mostly because it is devoid of the modern technological inventions and language. In the similar way, the unschooled young and adults, especially the ones that remained outside the boundaries of the modern educational systems, provide important insights into the authentic numerical abilities in humans. In particular, several researchers obtained important evidence from the indigenous people living in relatively remote and isolated locations. For instance, in absence of precise linguistic expressions for counting, Torres Strait islanders use body-based numeration (Ifrah, 1985). In other words, they use their own body as map to represent numbers. With their hands facing up, number 1 is represented on the right little finger, each finger counting up to number 5 mapped on the right thumb. Number 6 is embodied on the hand's wrist, number 7 on the right arm elbow, and number 8 on the right shoulder. Number 9 is placed on the sternum and transits to the numbers 10 to 17 on the left arm in symmetrical order to the right arm. Then, number 18 jumps to the left little toe up to 22 on the left big toe. Number 23 is on the left ankle, 24 on the left knee, 25 on the left hip, 26 jumps to the right hip, and the rest of the numbers continue down to number 33, which is conclusively mapped on the right little toe. For numbers larger than 33, Torres Strait natives use small sticks. This technique has been developed independently in some parts in Africa, Oceania, America as well as other places in the world.

The body-numeration uses tallying (recording of numerical scores) that is mapped in one-to-one correspondence to some external objects, in this case — the human body. The last tally in the set actually marks the cardinality of the complete set. Probably, the first tallying systems were purely visual, creating object icons to represent numbers. Specifically, possible grouping of the tallies in the iconic systems might have been the root of the non-iconic systems, which developed later in a complete symbolic representation of numbers (Wiese, 2003). In this way, one single sign can replace several grouped tallies, like in the example of the Roman numeral 'four', where IIII in written as "IV". Thus, the role of the language in the numerical cognition is indisputable, and through its symbolism and arbitrariness humans were able to develop very precise system of "symbolic tallies" that symbolize discrete quantities.

To pursue the issue of nonverbal numerical representation in humans, four prominent psychologists went in the heart of Brazil, to meet an Amazonian indigene group that speaks Mundurukú (Pica, Lemer, Izard, & Dehaene, 2004). This language has very limited lexicon for number related words, with number names only from 1 through 5. Pica et al. (2004) discovered that speakers of the Mundurukú language were able to compare and add large approximate numbers far beyond their naming abilities.

In the same year, Gordon (2004) studied the numerical presence in the language of Amazonian Pirahã tribe. Their language recognizes numerosities in the form of "one-two-many" and the cognitive performance on the quantities larger than three showed significantly poor results. Based on the data that showed constant coefficient of variation, Gordon (2004) concluded that the evidence is sufficient enough to suggest an analog estimation process, but emphasized the facilitating role of the language in the cognition of numerical magnitudes.

1.2 Psychophysical, perceptual, and cognitive evidence on numbers and magnitudes

Naturally, perceptual and cognitive systems of humans and animals possess abilities to estimate different environmental magnitudes. Both systems are crucial for successful survival of the behaviorally active organisms. Humans developed highly organized and meaningful notational system of numerals mostly used to express different discrete magnitudes. These symbols enable practical and conceptual calculations as well as estimations of varieties of environmental magnitudes to an enormous extent.

The central content of numbers is their magnitude. In this regard, numbers are quite different from the rest of linguistic symbols. In more detailed view, numbers hold general meaning of quantity, and more important, the degree of that quantity. For instance, we are able to calculate the sizes of the elementary particles in atoms or the vast distances between celestial bodies. The numbers are so precise in symbolizing magnitudes that even enable us to understand the concepts like infinity (e.g., the number π). Beside their symbolic form, numbers are extremely flexible and can be expressed in many other ways. In nature, they are non-symbolic and represented in sets of objects that can differ in identity, category, space, time, and so on.

Regardless of the form, numbers constantly maintain their magnitude and numerical information. Perhaps, because of this property numbers are located at the threshold of human perception, although they have to be extracted and inferred from the environment through other higher cognitive processes. Consequently, numbers can be studied on psychophysical, perceptual, and cognitive level. In addition, many generations of psychologists and neuroscientists were puzzled with the question of how numbers and their magnitudes are mentally and neurally represented. Finally, the astronomical patience and ingenious experimental designs in the past were fruitful to reveal the secret nature of numbers.

1.2.1 Continuous versus discrete quantities

It is well known that quantity is one of the fundamental properties of nature. Empirically, it exists in two main forms: continuos and discrete. This distinction is based on the concept of continuity, in which continuous quantities represent unbroken series, theoretically consisted of infinite number of elements. If a continuous quantity has a start and end points, than a chosen point anywhere on this continuum can assume any value, even up to an infinite precision. In contrast, discrete quantities represent series of distinct and successive elements and a particular point only assumes the assigned value of the particular element. To put it simply, continuos quantities are uncountable, whereas discrete can be counted.

Historically, cognitive scientists were curious to know how animals and humans sense and process both quantities. The debates were intensified when Davis and Pérusse (1988) proposed the so called 'last resort hypothesis' which stated that animals prefer stimuli with continuous magnitudes over stimuli that are numerical in nature. They believed that animals process numerical information only when the continuous cues are deficient. However, recent studies show that animals ranging from our distant ancestors up to more recent ones are very capable of representing and manipulating numbers. For example, Agrillo, Piffer, and Bisazza (2011) measured the proportion of correct choices of female mosquitofish that were trained to discriminate between and move towards either smaller or larger quantities. The discrimination was based on number cues, continuos quantities, or combination of both. It was found that fishes learn faster to discriminate when number and continuous dimensions were both accessible at the same time and there were no differences in the performance between number and continuous conditions separately, suggesting that fish were capable of using numerical cues as effectively as the continuous cues. Furthermore, our closer relatives *Macaca mulatta* spontaneously represent numbers and are better at matching numerical cues than cues coming from other perceptual dimensions like color, surface area, or shapes (Cantlon & Brannon, 2007). Equally, human infants discriminate smaller changes in numerosities when continuous variables are controlled for and they need bigger discrepancies between two surface areas for any change to be noticed when the set size remains constant (Cordes & Brannon, 2008). Similar to animals and infants, human adults seem to process both quantity dimensions independently. Barth (2008) investigated the relationship between cumulative areas of sets of disks and their numerosities and found no evidence for their interaction in a form of hypothesized Stroop-like interference. In other words, irrelevant dimension of number did not interfere with the relevant continuous dimension of disks' area which in turn even proved to be more difficult for comparison than numerical dimension.

1.2.2 Numerical precision, approximation, distance and size effects

Enumerating collection of four objects or less is rapid and precise (*subitizing*). On the contrary, enumerating four or more objects is much slower and prone to errors (Feigenson, Dehaene, & Spelke, 2004; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982). It is obvious that human cognitive abilities in numerical precision are quite limited. The relation between numerical precision and approximation is negative, i.e., as the collection grows larger, extracting precise numerical information takes greater cost.

Moyer and Landauer (1967) reported two behavioral effects that are intimately related to the numerical quantification. For a brief time they presented pairs of Arabic numerals and sim-

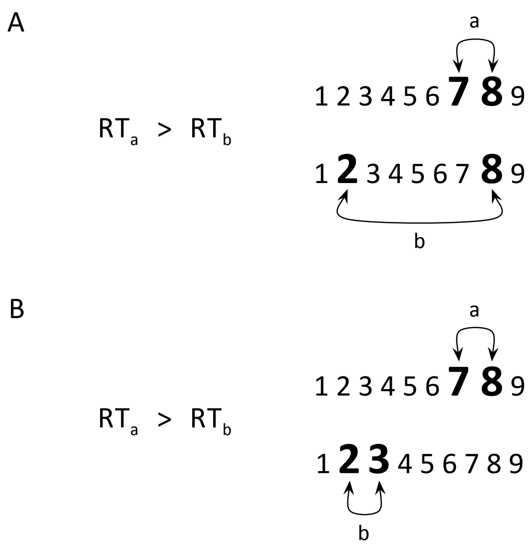

Figure (1.1) **Illustration of distance and magnitude effects. (A)** People are faster to decide which numeral is smaller/larger when two numerals are numerically far apart. **(B)** As numbers are getting larger and numerical distance is kept constant, it takes more time to respond to make smaller/larger judgment.

ply asked their participants to decide which one is larger by pressing one of the corresponding buttons. This simple task revealed surprising results. As the numerical distance increased between the two numerals, the response times became shorter . For example, participants were faster to identify the larger number in the pair 2 and 8, while it took longer to identify it in the pair 8 and 9. Eventually, this phenomenon came to be known as *classical distance effect* (Figure 1.1, A). Additionally, larger numerals required longer comparison times in contrast to the smaller ones, and pairs like 2 and 3 were processed faster than pairs like 8 and 9, or in other words, *size or magnitude effect* (Figure 1.1, B). In short, the larger the two numerals and the smaller the distance between them, it takes more time for the participants to decide which one is larger. Moyer and Landauer (1967) also concluded that the mental numerical magnitude obeys Weber's law (the difference threshold, i.e., the smallest difference between two magnitudes that person can detect, is defined by the ratio of the magnitude sizes).

A different kind of numerical distance effect has been identified in the studies that employ priming paradigm. In contrast to the "classic" distance effect that emerges when people make smaller/larger numerical judgments, another kind of *priming distance effect* occurs when people perform lexical decisions or name numerals (den Heyer & Briand, 1986; Reynvoet, Brys-

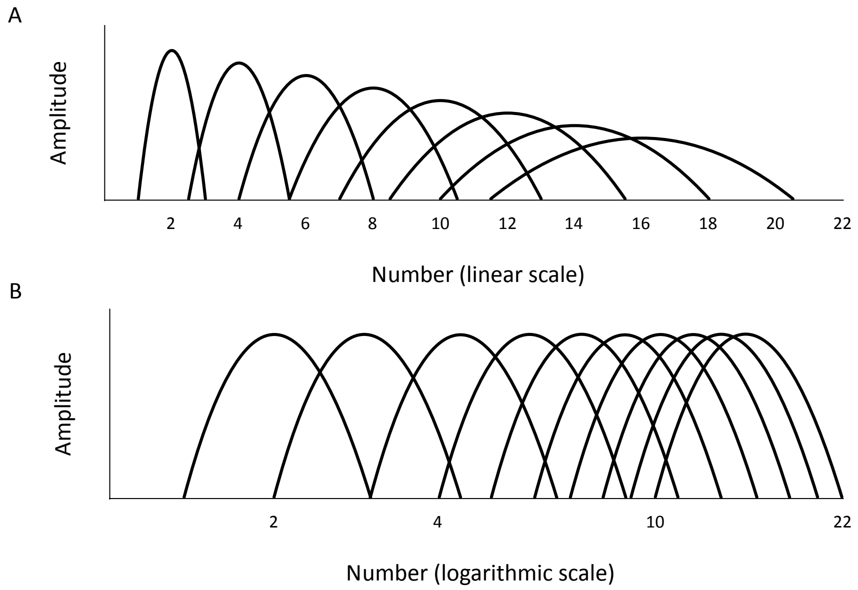

Figure (1.2) **Two models of analog mental number line.** **(A)** Scalar variability (Gallistel & Gelman, 2000). **(B)** Compressed line (e.g., Brysbaert, 1995; Dehaene, 1992).

baert, & Fias, 2002). Here, when prime's numerical value is equal or close to the target's one, the performance in lexical tasks on targets is enhanced. For instance, people are faster to identify the numeral 5 if it was preceded by 4, and as the value deviates further from the target, its latencies are getting larger.

Although the classical and priming distance effects appear diametrically opposite, they are outcomes of the same underlying *mental number line* (MNL; Moyer, 1973; Moyer & Landauer, 1967; Restle, 1970). It is believed that the numerical units are mapped onto MNL through overlapping distributions and this explains numerical distance and magnitude effects. For example, the choice between 2 and 3 takes longer than 2 and 8 because distributions of the first pair overlap significantly more than distributions of the second pair (Figure 1.2). However, in order to explain magnitude effect, distributions of numerical units cannot be fixed and linearly organized within the mental number line. Instead, two propositions for their organization have been put forward. First one assumes scalar variability in mental number line where with the growing magnitude of numerical units, separate activation distributions of each number on the line are getting increasingly platykurtic (Gallistel & Gelman, 2000, Figure 1.2, A). Second proposition suggests compressed mental number line (e.g., logarithmic scale) in which distributions of the units may have equal kurtosis, but they increasingly overlap as magnitude increases (e.g., Brysbaert, 1995; Dehaene, 1992, Figure 1.2, B).

In the classical distance effect, smaller overlap of the distributions of each number represented on the line leads to better performance and numerically distant numbers are easier to compare. In the priming distance effect, neighboring numbers are semantically close and when one of them is activated, neighbors receive part of that activation and benefit from their pre-activated stage (for extended theory on the spreading activation in priming see Collins & Loftus, 1975).

1.2.3 Early numerical magnitude activation

Is numerical magnitude automatically activated? Is it possible to suppress it? The short answer is: unlikely. Henik and Tzelgov (1982) asked 26 participants to compare which of the two numerals is larger either in numerical or physical font size (e.g., 2 5). The overall response times for the physical comparisons were faster, but the numerical magnitude (i.e., semantic dimension of the stimuli) interfered in the process. In particular, when the numerical and physical sizes were incongruent (e.g., 3 5), it took longer to identify which numeral is physically larger. On the other hand, this wasn't true in the congruent condition (e.g., 5 3) where responses were faster and accurate. This amazing finding shows early and automatic activation of the numerical magnitude even when such activation isn't required.

Moreover, automatic activation of numerical magnitude is evident even when people compare numerals from memory. The participants in an earlier study visually memorized set of four numerals displayed briefly for 500 ms (e.g., 8-7-6-5; Morin, Derosa, & Stultz, 1967). Next, another single numeral appeared as probe (e.g., 1) and the task was to answer "yes" if the probe was present in the memorized set, and "no" if it was absent. The further apart was the probe from the smallest numeral in the set, the faster the response times (distance effect). In this case too, although the task required simple memory recollection, numerical magnitude automatically activated and had an effect on the recall response times.

1.2.4 Spatial numerical/musical/temporal/quantity associations of response codes (SNARC/SMARC/STEARC/SQUARC effects) and A Theory of Magnitude

In the literature of the numerical cognition it is already widely accepted that the numbers are spatially represented. One of the most interesting findings in the field is the SNARC effect (*Spatial-Numerical Association of Response Codes*) described in the influential study by Dehaene, Bossini, and Giraux (1993). Participants in the study judged the odd-even parity of the Arabic numerals 0 to 9, and although irrelevant to the task, numerical magnitude automatically influenced the response times. Smaller numerals were responded to faster with response codes on the left, in contrast to the larger numerals that were faster with response codes on the right (see also Gevers & Lammertyn, 2005; Wood, Willmes, Nuerk, & Fischer, 2008). On the mental number line, numbers seem to be represented on spatial continuum with small magnitudes towards the left side, and large magnitudes towards the right.

In addition to the SNARC effect, several similar effects were reported in the literature and all of them reveal spatially coded magnitudes. For instance, in the SMARC effect (*Spatial-Musical Association of Response Codes*) responses with the left key are faster for low-pitch sounds, while the right key responses are faster for the high-pitch sounds (Lidji, Kolinsky, Lochy, & Morais, 2007; Nishimura & Yokosawa, 2009; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). The left-to-right ascending spatial coding of the magnitude extends in the temporal domain too, as shown in the STEARC effect (*Spatial-Temporal Association of Response Codes*; Ishihara, Keller, Rossetti, & Prinz, 2008). This effect was observed when Ishihara et al. (2008) instructed their participants to respond with horizontally aligned buttons to eight sequential auditory clicks, each fixed to 500 ms. However, the last probe click was different from the previous seven and varied between early and late onsets ($\pm$ 215 ms). The task was to judge the onset of the eighth audio click. The early onset times elicited faster responses with the left key and the late onsets faster responses with the right key.

The behavioral data from the three effects suggest shared, spatially coded mental representations of magnitude in the numerical, auditory, and temporal domains. This similarity intuitively suggests that the mental magnitude representation could be generalized. In other words, there may be a broader representational system of magnitude, which processes any quantitative information equally, regardless of the input. Gallistel and Gelman (2000) provide evidence from animal subjects for shared mental magnitudes. In their opinion, countable and uncountable quantities require arithmetical combination of both for the animal to be able to make any behavioral decision in the environment where space and time are intertwined. This notion motivated Walsh (2003) to review a long list of different studies coming from disciplines like cognitive psychology, neuropsychology, cognitive neuroscience, brain-imaging, developmental psychology, as well as research on animal subjects, and to summarize the findings in a single unifying theory named *A Theory of Magnitude* (ATOM). The theory argues for common processing mechanism of temporal, spatial, and numerical magnitudes, located in the parietal cortex. The behavioral action is the link that connects the three magnitude types (Rossetti et al., 2004; Walsh, 2003).

Furthermore, considering the countable and uncountable quantities as part of a common magnitude system, Walsh predicted that SNARC effect should be an instance of a general quantity effect — SQUARC effect (*Spatial-Quantity Association of Response Codes*). In other words, both discrete and continuous magnitudes share the same or similar mental representations.

1.3 Theoretical concepts, models, and brain regions involved in numerical processing

Historically, there have been many attempts to model number concept. Some of the models considered only the cognitive aspect, but some others described neuroanatomy and neurophysiology of numbers as well. However, it is still an ongoing debate how numbers are processed and represented by the brain and scientist haven't reached general consensus yet. Next sections will describe some of the most influential models currently, together with contextual categorization of numbers.

1.3.1 Cardinal, ordinal, and nominal numbers

The following sentence demonstrates the extreme flexibility of numbers: "Despite a seventy-eight yard run by number thirty-four the Bears lost by two touch-downs and dropped into sixth place" (Fuson & Hall, 1983, p. 49, as cited in Wiese, 2003). Depending on the way numbers are assigned to objects and events, there are cardinal, ordinal, and nominal numbers. Cardinal numbers denote total sum (size) of collection of items, regardless of their quality. In the sentence above 'seventy-eight yard' and 'two touch-downs' are examples of cardinal numbers. On the other hand, ordinal numbers emphasize single item in a set or sequence, and convey its position in relation to the other members. The phrase 'sixth place' is an example of ordinal number. Finally, nominal numbers name objects and events and are devoid of numerical magnitudes. In the sentence, 'number thirty-four' represents the identity of one of players in the team. Nominal numbers are everywhere around us, serving useful function of signifying buses, streets, buildings, telephone numbers, ID cards, etc (for more see, Wiese, 2003).

1.3.2 Semantic context and Arabic numerals

It has been said that context changes the meaning of words. Their contextual dependency is so substantial that words like *cast* transform from a noun (e.g., object made of molten metal, *bronze statue*) into a verb (*to throw*). In order to understand this phenomenon, several accounts have been proposed in the literature on how semantic context modulates the meaning of the words. Most can be summarized in three hypotheses: *strong selective access*, *non-selective access*, and an intermediate *weak selective access* (Schvaneveldt, Meyer, & Becker, 1976). First hypothesis assumes that when a word is presented in an ambiguous circumstances and several of its meanings are competing for an activation, the additional contextual cues aid the selection of only one of the meanings a priori very early in the process, prior to the activation of all alternative meanings. In contrast, the non-selective access hypothesis states that after the word recognition has been completed, all meanings are simultaneously activated and the context is used a posteriori in the later stages to select one of the multiple activated alternatives. Somewhat intermediate position is taken by the third hypothesis in which all meanings of one word are activated after its recognition, but the semantic context aids selection of one only if it is strictly related to that particular meaning. When context is not present, the access of one of the meanings is random.

All three hypotheses assume that words have at least two meanings and that one meaning has to be selected at the end of each linguistic operation in which an ambiguity is introduced. Unlike most words, Arabic numerals and their verbal and written forms seem to refer to only one meaning taken from a continuos line of quantities. Thus, contextual influence on Arabic numerals, if any, could be assumed to have effects of facilitation or inhibition on the single numerical meaning. That is, a particular number expresses only a single, weak or no meaning at all and if we attempt to classify numbers based on context, we will be tempted to classify them according to their degrees, not qualities. As a results, one contextual categorization would include the full meaning of numbers, other would encompass numbers with partially activated meanings and finally, numbers that are accessed without direct reference to their magnitude would fall within a category of non-semantic numbers.

1.3.3 McCloskey's model, Encoding-complex hypothesis, and Dehaene's triple-code model

McCloskey and his colleagues developed a model with attempt to explain the cognitive numerical processes, calculations and executions (McCloskey, 1992; McCloskey, Caramazza, & Basili, 1985, 1986, Figure 1.3, A). The model is built upon neuropsychological research on dyscalculic patients. It assumes abstract numerical representation integrated by several notation-specific modules for numerical comprehension and production. In this model, numerical calculation and processing are performed within amodal number representation, which is the central mediator between the numerical inputs and outputs. Particularly, McCloskey's model describes sequential numerical processing where all numerical notations (e.g., Arabic numerals, verbal numerals, roman numerals, non-symbolic numbers, etc.) are converted through a comprehension module into a single, modality-independent abstract format and processed exclusively via the amodal internal representation. For example, when Arabic numeral is read aloud or written in letters, it is believed that the arabic representation of that numeral has been transcoded into verbal code and to its matching verbal numeral (e.g., Arabic "2" transforms into written "two" or phonological [ˈtuː]). Lastly, magnitude representation provides meaning by assigning corresponding quantitative information to Arabic and verbal numerals. Finally, the production module takes over and delivers the numerical output in the required form and notation. In addition, there are two important points that should be emphasized. First, this model involves and promotes mental numerical representation as a concept in the cognitive theories of numbers. Second, all different numerical notations undergo transformation into a single amodal representation, which in practice generates a testable set of

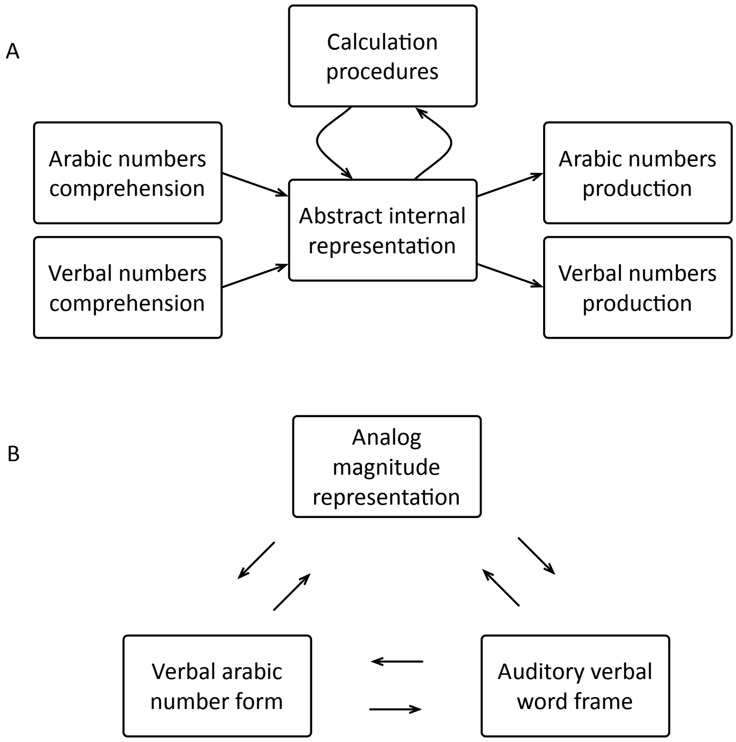

Figure (1.3) **Two numerical models.** **(A)** Diagram of McCloskey's model. **(B)** Diagram of Dehaene's triple-code model (reproduced from Cohen, Dehaene, & Verstichel, 1994)

hypotheses.

In contrast to McCloskey's model, the *enconding-complex hypothesis* (Campbell, 1994; Campbell & Clark, 1988) abandons the idea of abstract, amodal numerical representation (McCloskey, 1992; McCloskey et al., 1985). Instead, Campbell and Clark (1988) propose parallel network of format-specific codes for numbers (e.g., visual, verbal, symbolic, non-symbolic, etc.). All codes are interactive and associated with each other. The numerical comprehension, calculation, and production are achieved by the integration of format-specific codes in the network. At the same time, each code competes to dominate in the network and depending on its strength, it will activate higher cognitive information that will lead to specific numerical production, as in the authors' words:

> [...] a visual feature analysis activates hypotheses about the identity of each digit, with higher order information related to the candidates (e.g., phonological codes,

> semantic categories and relations, specific associations) also becoming available. The resulting encoding complex includes various phonological candidates whose strength depends on the amount of priming from visual, semantic, associative, and procedural connections among the multiple representations activated. (Campbell & Clark, 1988, p. 209)

Meanwhile, another model appeared in the literature that aimed to overcome the limitations of McCloskey's model and the encoding-complex hypothesis. The *triple-code model* received a lot of attention by the researchers in the field of numerical cognition and it is currently one of the most popular models (Dehaene, 1992, Figure 1.3, B). First, this model is combination of both, McCloskey's model and encoding-complex hypothesis. Second, the model does not assume single central number representation, and in that respect it is more similar to the encoding-complex hypothesis. Third, triple-code model assumes that numbers are mentally represented in three different codes: the *visual number form*, the *verbal word frame*, and the *analog magnitude representation*. Each code belongs to distinct functional modalities. The visual and verbal codes have specific notations and are dependent on their modalities, whereas the analog magnitude representation is modality-independent. The three codes are interconnected through transcoding procedures and they can be easily transformed into one another. However, not every numerical processing will gain access to the analog magnitude. For example, arithmetic facts (e.g., multiplication table rules), verbal counting or simple calculations, autonomously activate the verbal code without engaging the code for analog magnitude. On the other hand, procedures like numerical comparison, number approximation and estimation, and parity judgment will activate the analog magnitude code. Later, Dehaene and Cohen (1995) expanded the triple-code model with new findings from the neuroanatomical research and brain imaging. In this manner, the model extended its framework from cognitive towards the neuroanatomical domain. With the expansion, different neural substrates were associated with the three codes. The visual number form is processed bilaterally in the occipito-temporal regions, with somehow limited processing capacity for the right hemisphere in comparison to the left one. The analog magnitude representation involves several cortical areas in the parieto-occipito-temporal junction of both hemispheres, with possible dominance of the right hemisphere. The linguistic properties of the verbal word frame involve regions in the left hemisphere, precisely inferior frontal, superior and middle temporal gyri as well as basal ganglia and thalamic nuclei. Additionally, the arithmetic facts and some simple calculations rely on the language areas in the left hemisphere. Generally, all regions associated with the three codes communicate with each other through dedicated pathways, except for the visual and magnitude codes, which exclusively communicate within the right hemisphere.

1.3.4 Neuropsychological aspects of numbers

Losing a brain function due to some disease or accident can have serious consequences on the behavior. After damage in the left angular gyrus (Brodmann area 39), set of deficits appear in writing, left-right orientation, calculation, and finger recognition. All these deficits are collectively known as *Gerstmann's syndrome*, after the Austrian neurologist Josef Gerstmann (Gerstmann, 1940). Obviously, when loss of several functions follows some brain damage, it is almost certain that these functions are related. Gerstmann's syndrome demonstrates that there is a certain relation between space, numbers, fingers, and writing. The most speculated brain areas that subserve numerical processing are the intraparietal sulcus (IPS), left angular gyrus, and superior parietal lobe (Bueti & Walsh, 2009; Dehaene, Piazza, Pinel, & Cohen, 2003, 1996; Nieder & Dehaene, 2009; Walsh, 2003). The position and interconnection of these structures are ideal location for the "number sense" (Dehaene, 2011). Single-neuron recording studies in primates provide evidence for the involvement of lateral prefrontal cortex (lPFC) in the processing of quantitative information (Nieder, Freedman, & Miller, 2002).

Furthermore, the diversity of brain areas involved in numerical processing is reflected in selective impairments seen in patients with brain lesions. Many neuropsychological studies report that those patients often have preserved numerical abilities for one sort of operations, but not for other. For example, Cipolotti and Butterworth (1995) report a case of a patient S. A. M. who showed relatively preserved numerical understanding, but his number production skills were largely compromised. S. A. M. failed to read aloud digits or written number words, to convert written numeral to Arabic numeral, or to write down Arabic numerals that were dictated to him. Surprisingly, this patient could repeat numbers and showed preserved ability to produce answers in a form of Arabic numerals to written arithmetical problems. Likewise, Cohen, Dehaene, and Verstichel (1994) described a deep dyslexic who was subjected to series of reading tasks consisted of words and non-words, coupled with familiar and unfamiliar numerals. The patient couldn't name unfamiliar numbers, although several tests for number comprehension revealed intact quantitative numerical processing. On the other hand, this patient performed much better when asked to name familiar numerals, producing 38 out of 52 meaningful answers (73%). Still, patient's answers seemed to be retrieved as "facts" which is illustrated in the response for 504 "the number of the cars that win… it was my first car… it begins with a P… Peugeot, Renault… it's Peugeot… 403… no, 500… 504!" (Cohen et al., 1994, p. 272). Apparently, familiar numbers were stored as nominal facts and associated to other types of semantic knowledge like car models, a phenomenon that fortunately spared patient's reading of Arabic numerals to some extent.

In a similar study that provides further evidence on dissociate cerebral networks for fact retrievals and manipulation of quantities, Dehaene and Cohen (1997) analyzed an acalculic patient that manifested clinical features of Gerstmann's syndrome. Patient MAR suffered from lesion in the inferior parietal lobule and showed severe disabilities in quantitative processing. Non-cardinal uses of numbers were largely left intact, and in 80% of cases this patient was able to provide correct meaning of familiar numerals that were read aloud to him. Also, when arithmetical operations were presented in familiar form (not abstract) like hours of the day, MAR was able to process numerical meaning adequately. On contrary, when numerals were presented in unfamiliar (abstract) form (e.g., in arithmetic notation like 2 + 15), patient wasn't able to give the correct response to any of the questions. To sum up, evidence from neuropsychological studies points to a complex system of inter-related brain regions that subserve perception and cognition of numbers. Any damage in any of them, potentially leads to selective impairments in numerical abilities.

2

The Dynamics of Quantity Representation — Is there a SQUARC Effect?

Walsh (2003) predicted SQUARC effect (Spatial-Quantity Associations of Response Codes) in ATOM theory (A Theory of Magnitude). The author believed that many other effects like SNARC, SMARC, STEARC, etc., in which magnitudes are represented spatially are part of the same family of effects. Therefore, defining one general effect that encompasses all seems reasonable idea. In simple words, small and large quantities regardless of their quality should show spatial preferences.

2.1 Pitch and loudness do not elicit spatial mapping of their magnitudes: No evidence for the SQUARC effect

The processing of quantitative information is one of the most remarkable abilities of the brain. Most of the knowledge on how the brain represents and processes quantitative information comes from the field of numerical cognition. Within this research body, the cardinal aspect of numbers received most of the researchers' attention and new interesting findings are published every day in many scientific journals. Cardinal numbers are most intriguing because of their semantic flexibility. When we ask the question of how many, we expect to obtain a cardinal numerical answer (Wiese, 2003). First of all, cardinal numbers encode quantitative information that is comprehended and interpreted through magnitude processing mechanism in the brain. Generally, the term *magnitude* is used interchangeably with *quantity*, but in a subtle terms, magnitude will also denote the level of present quantitative information within the mental quantity processor (Dehaene et al., 1993). Second, the nonverbal magnitude processing abilities are common for animals, infants and adult humans (Brannon, 2006; Cantlon, Platt, & Brannon, 2009; Nieder, 2005). "Nonverbal" in this case is absence of language facilitation on the magnitude processing, which is valid for the non-verbal animals, preverbal humans, and in adults with language comprehension and production disabilities. Only through the use of language we can extract (enumerate) discrete magnitude points from the analog magnitude representation in the brain (Dehaene, 2011).

Currently, there are three popular models of numbers. McCloskey's model, encoding-complex hypothesis and Dehaene's triple-code are relatively different from each other, but similar in assuming analog magnitude processing mechanism in the brain. All three models adopt mental quantity representation with certain degree of independence from the numerical inputs and outputs (Campbell & Clark, 1988; Dehaene, 1992; McCloskey et al., 1985). The assumption of independent magnitude processor opens space for discussion whether different modality inputs cross-communicate between each other and share that processor. Indeed, Xuan, Zhang, He, and Chen (2007) showed that the judgments of temporal durations can be affected by non-temporal magnitudes. In a Stroop-like paradigm, for a brief time participants observed pair of stimuli and judged which one lasted longer. The non-temporal stimuli involved Arabic numerals, dot arrays, open squares with different sizes, and solid squares with varying luminance. The temporal judgments were directly affected by the magnitude of the stimuli, where the large magnitudes were judged to last longer and vice versa. Moreover, Oliveri et al. (2008) reported another example of crossmodal magnitude interaction between numerals and time. In their study, ten participants compared the duration of numerical stimuli (1, 5, and 9, with varying duration 250 and 350 ms) to a reference with fixed duration (numeral 5, duration 300 ms). The results showed that the presentation of low numeral '1' was judged to last shorter than the presentation of the high numeral '9'.

The time is not the only dimension that interacts with the numerical magnitude. Different types of magnitudes also affect spatial perception. For instance, there are several effects in the literature that associate low magnitudes with the left, and high magnitudes with the right space. These associations can be spatial-numerical (SNARC effect; Dehaene et al., 1993); spatial-musical (SMARC effect; Lidji et al., 2007; Nishimura & Yokosawa, 2009; Rusconi et al., 2006); or spatial-temporal (STEARC effect; Ishihara et al., 2008). Finally, ATOM (A Theory of Magnitude) summarizes the research findings on numerical and other types of magnitudes under one theoretical framework (Bueti & Walsh, 2009; Walsh, 2003). According to this theory, common magnitude system binds together time, space, and quantity. The binding agent for all is the action, since all behavior happens in certain location and time, and involves estimation of quantitative information. Additionally, it predicts that all spatially mapped magnitudes are instances of a general SQUARC effect (Spatial Quantity Association of Response Codes).

The present experiment attempted to connect crossmodal quantity interactions with the notion of a "mental quantity line" (Kirjakovski & Utsuki, 2012). The experimental hypothesis stated that SQUARC effect would be evident in the detection of target into the visual modality, after a presentation of sounds with varying pitch and loudness (low vs. high magnitude) in the auditory modality. In other words, targets on the left within the visual modality will be detected faster after presentation of auditory cues with low magnitudes, and the detection of the right targets will be facilitated by prior auditory cues with high magnitudes.

2.1.1 Method

Participants. Four males and six females from Kobe University with total mean age of 22.1 participated in the experiment. Their handedness was determined by the *Edinburgh Inventory* (Oldfield, 1971) and all were right-handed. All participants reported normal or corrected-to-normal vision, coupled with normal hearing.

Stimuli and procedure. In this experiment, a modified version of the spatial cueing paradigm was used (Fischer, Castel, Dodd, & Pratt, 2003; Posner, 1980; Posner, Snyder, & Davidson, 1980). In the classical version of the paradigm, stimuli are typically presented visually in the center between two locations (left and right). In one of these locations a target appears after

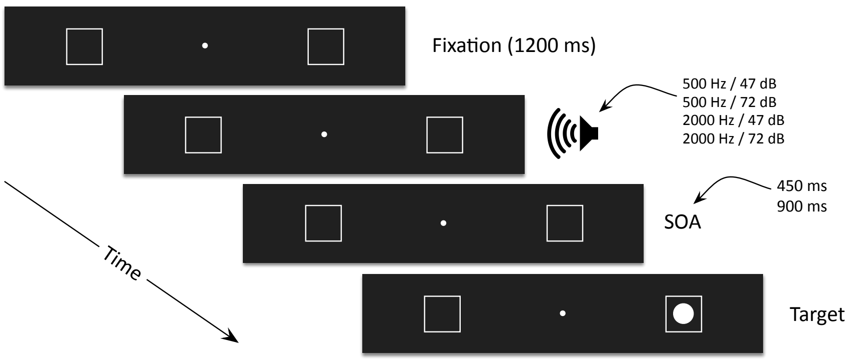

Figure (2.1) **Graphical description of the experimental procedure in the crossmodal SQUARC experiment.** Participants were tested with a modified version of the classical spatial cuing paradigm. Each trial started with fixation point lasting for 1200 ms, after which auditory stimuli (monophonic pure sounds) played through headphones for 1500 ms. After a variable stimulus onset asynchrony (SOA), the participants responded with button-press when target appeared in one of the lateral squares.

the central stimulus offset. Participants are required to make response (usually button-press) as soon as the target appears in one of the locations. The response time between the onset of the target and the participant's response is measured.

In the context of current experiment, visual stimuli were replaced with four monophonic auditory cues (pure tones) that varied in pitch and loudness (Table 2.1). The idea was to present analog magnitudes in the auditory and to record response times in the visual modality.

Each trial started with central fixation point (0.2° in diameter) placed between 2 white squares (each had 10° eccentricity from the fixation point and 2° width). The target was a white circle (1.4° in diameter). All stimuli were presented on a black background. During one trial, participants were fixating the point in the center of the computer screen (their heads were resting on a chin rest). Auditory stimuli were randomly delivered through headphones. All they could hear was a monophonic sound, followed by a visual target that appeared left or right in one of the two squares on the screen (Figure 2.1). Their task was to press keyboard button as soon as they detected the target. The trials started with fixation (1200 ms), followed by one of the sounds (1500 ms), and target appeared after a stimulus onset asynchrony (SOA) of 450 ms or 900 ms. Each participant accomplished 112 (87.5%) real trials and 16 (12.5%) catch trials where no target appeared. The error rate was negligible.

Stimuli	Values
Pitch	500 or 2000 Hz
Loudness	47 or 72 dB ($\pm$1)
Stimulus onset asynchrony (SOA)	450 or 900 ms

Table (2.1) **Details of the stimuli used in the crossmodal SQUARC experiment together with the stimulus onset asynchronies (SOAs).** The asynchronies were added with purpose to increase participant's vigilance and to avoid a possible rhythmic responding (if trials have had fixed duration).

2.1.2 Results

The mixed 2 $\times$ 2 $\times$ 2 ANOVA (Pitch [500 Hz, 2000 Hz] $\times$ Loudness [47 dB, 72 dB] $\times$ Target [Left, Right]) with repeated measures on all three factors showed significant main effect only for loudness $F(1,9) = 5.873, p < .05$ (Table 2.2). Other main effects, and importantly the interactions between pitch, loudness, and the spatial location of the target were not statistically significant (Table 2.2, Figure 2.2).

Additionally, several paired t-tests showed slower response times after SOA of 450 ms, and faster response times after 900 ms, $t(9) = 2.526, p < .05$ (Figure 2.3, A). Furthermore, slower response times were registered for stimuli with 47 dB of loudness in contrast to the ones of 72 dB, $t(9) = 2.361, p < .05$ (Figure 2.3, B). Finally, at alpha level of .10, low pitch stimuli (500 Hz) elicited faster responses than high pitch stimuli (900 Hz), $t(9) = 1.837, p < .10$ (Figure 2.3, C).

2.1.3 Discussion

Although the two auditory dimensions (pitch and loudness) varied between low and high magnitudes, no significant spatial preference was evident in the visual modality. According to the hypothesis in this experiment, if the auditory cues really activated mental quantity representation with spatial left-to-right orientation in the auditory modality, we would expect an interaction between the magnitude and extracorporeal space in similar left-to-right manner within the visual modality as well. In that case, similar to SNARC, SMARC, STEARC, SQUARC, and other space-magnitude interaction effects, response times would be faster when the magnitude and the target are congruent i.e., when low magnitude is mapped towards the

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	9	570.030	.000
Pitch	1	9	3.353	.100
Loudness	1	9	5.873	.038*
Target	1	9	2.602	.141
Pitch × Loudness	1	9	1.200	.302
Pitch × Target	1	9	.118	.739
Loudness × Target	1	9	.663	.437
Pitch × Loudness × Target	1	9	2.841	.126

Table (2.2) **Results obtained with the analysis of variance in the crossmodal SQUARC experiment.** A significant main effect at alpha level of .05 was observed only for loudness (Figure 2.3, B), while the main effect of pitch was significant at alpha level of .10 (Figure 2.3, C). The interaction between pitch, loudness, and target was approaching significance.

left side of the space, and the high magnitude towards the right. For example, high pitch/high loudness should facilitate faster response times when the visual target appears on the right. The same would be true for the low pitch/low loudness and the target on the left. However, such observation wasn't evident in this experiment, leading to the conclusion that there were

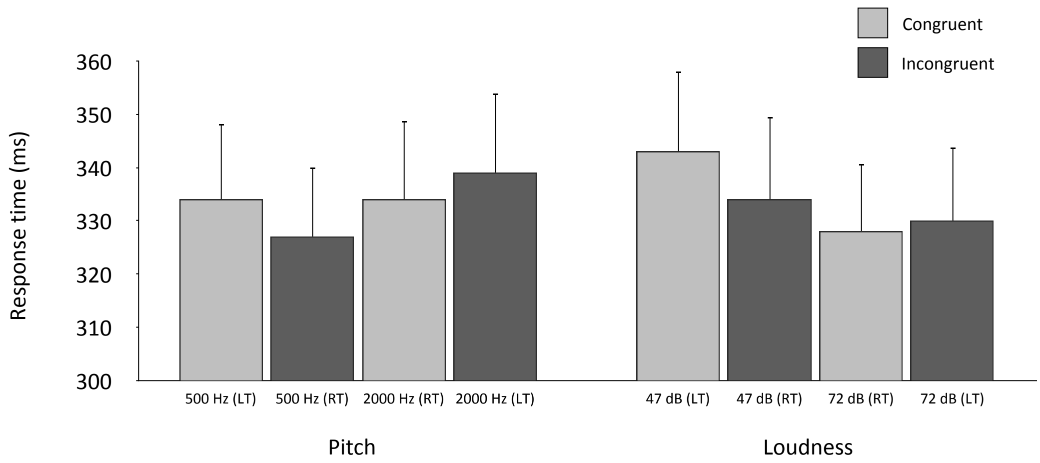

Figure (2.2) **Bar chart representing congruent and incongruent conditions as a function of the SQUARC hypothesis.** Here are shown the interactions between Pitch, Loudness, and the Target (left target — LT, right target — RT). Error bars illustrate the standard error of the mean.

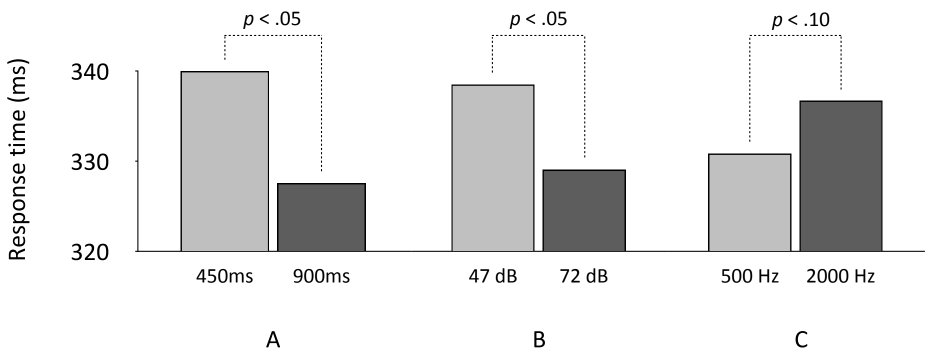

Figure (2.3) **Bar charts illustrating differences between variables in the crossmodal SQUARC experiment.** **(A)** Stimulus onset asynchronies (450 ms vs. 900 ms); **(B)** Low/high loudness values (47 dB vs. 72 dB); and **(C)** Low/high pitch values (500 Hz vs. 2000 Hz).

no statistically significant spatial mappings of the pitch and loudness to the left/right target in the visual modality (absence of SQUARC effect).

Despite the lack of support for the main hypothesis, Figure 2.2 shows that interactions between pitch, loudness, and target location are not random. Instead, low pitch and loudness magnitudes manifest tendency for faster response times for the target on the right (reversed SQUARC effect), while the high magnitudes remain congruent with the hypothesis (SQUARC effect). This tendency, although statistically insignificant, at least suggests that to some extent, auditory magnitude influenced the detection of targets in visual modality in an organized manner. Intuitively, the small sample size of just ten participants in this experiment may be a contributing factor for the lack of statistical support for the findings. Additionally, within the loudness condition, participants took conservative approach and stimuli with 47 dB were processed slower compared to 72 dB stimuli (Figure 2.3, B). The same was true for the two SOAs where the shorter SOA produced longer response times (Figure 2.3, A).

There are two reasonable explanations that have a potential to explain the absence of SQUARC effect in the current experiment. First of all, although the task in this experiment combined the three components — pitch, loudness, and spatial location of the target, it may have failed in the unitary action that binds them all. In other words, participants may have seen the auditory cues and visual target as separate, independent events. Remarkably, multisensory integration is dependent on the allocation of attention to the both modalities (Talsma, Doty, & Woldorff, 2007; Talsma & Woldorff, 2005). Because of the relatively longer SOAs between the auditory cue and the presentation of the target, it is possible that participants attended one modality at the time and disassociated both events. Under the presumption that auditory stimuli activated a magnitude representation for either pitch or loudness, still the disassociation between the auditory cue and the target may have prevented robust crossmodal exchange between the magnitude and the spatial location of the target. The second explanation involves magnitude comparison and judgment tasks as procedures for magnitude activation. In particular, some of these procedures are *parity judgment task* (Dehaene et al., 1993; Nuerk, Wood, & Willmes, 2005); *magnitude comparison task* (Müller & Schwarz, 2008); *mental number bisection, physical line bisection,* and *landmark task* (Cappelletti, Freeman, & Cipolotti, 2007); *visual size discrimination task* (Gallace & Spence, 2006); *speeded discrimination task* (Marks, 1987); *timbre discrimination task* (Lidji et al., 2007); etc. Comparison procedures involve a reference point and measurement that estimates distances from that reference point. In current experiment the reference point was missing, and therefore comparison process didn't occur because there wasn't anything to compare or measure. Thus, any bisection, judgment or comparison would be compulsory prerequisite for the numerical or any other non-numerical, continuous magnitude to become active.

In summary, the experimental procedure didn't provide sufficient evidence for the existence of crossmodal SQUARC effect. Nevertheless, some of the trends in the data suggest at least a relation between the magnitude in auditory modality and spatial location in the visual one. This does not necessarily conform to the scheme of SQUARC or other similar effects. Also, few additional findings shed light on the processing duration differences between low/high pitch and loudness as well as different stimulus onset asynchronies. Finally, the outcome of this experiment may be due to the dissociation between auditory cues and visual target, i.e., both events were perceived as separate and mutually independent. The other reason may be the absence of comparison, judgment, or bisection procedures. These types of procedures activate the analog mental representation of quantity and lead to spatial magnitude mappings. All three procedures imply a reference point that could be either physical (perceptual) or mental (cognitive). Without this reference, comparison procedures cannot be initiated at first place, and the activation of the mental representation of magnitude will not occur.

3

The Effects of Context on Numerical Representations

The development of outstanding human ability to communicate through spoken and written language affected many perceptual and cognitive domains including number competence. While other species and pre-verbal infants can make exact number estimations up to four, through the use of language virtually any given quantity can be communicated precisely in typical adults. Also, context plays important role of assigning situational meaning to sentences and sometimes changes the meaning of words completely. Given that Arabic numerals are part of the modern language, it is interesting to find out how contextual information influences their processing.

3.1 Cardinal and nominal contextual priming in a comparison-to-standard task

How does context influence numerical processing? Are numerals in nominal and cardinal contexts equally represented? Do people activate same mental processes when they distinguish between price tags in a store and postal codes on their envelopes? Indeed, questions like that show that the processing of analog and digital quantities is not a trivial issue at all. Even more, due to lack of research papers, question on numerical context is relatively challenging to answer. The following experiments will try to approach the problem of numerical context and possibly provide some experimental evidence that will clarify the issue.

A good way to start the analysis is to take some hints from the abundant research on number notations. It has been postulated that number information is denoted in three main representations: Arabic, verbal, and magnitude (Dehaene, 1992; Dehaene & Cohen, 1995; Fias, Brysbaert, Geypens, & D'Ydewalle, 1996). Naturally, processing latencies and other qualitative differences vary between different notations. For example, Fias, Reynvoet, and Brysbaert (2001) showed that the presence of numerically incongruent Arabic distractor does not affect the naming of the written numeral presented at the same time, which was taken as evidence that written numerals can be named asemantically. On the other hand, much bigger debate has developed over the issue whether Arabic numerals can be named without access to their magnitude. Fias et al. (2001) also found the opposite pattern in which number words served as distractors and interfered when participants had to name Arabic targets. This pattern is very similar to the one found in picture naming where it is impossible to name a picture if the meaning is not comprehended, whereas words are readily named without access to their meaning (Glaser, 1992). When words and pictures are simultaneously presented, semantically congruent pictures don't interfere with the process of reading words aloud, but the congruent words impede picture naming. In a similar manner, Fias et al. (2001) reported that Arabic numerals are processed in pictorial manner and the activation of their meaning is compulsory, while written number forms don't necessarily require access to their semantics in order to be named. In other words, simultaneously presented Arabic numeral does not obstruct the overt reading of the written numeral, but naming aloud Arabic numeral is obstructed by the written numerals.

Other studies looked further for an answer whether Arabic numerals can be processed without direct access to their semantics. Models of word comprehension and production predict that digits, similar to written words, can achieve direct conversion to phonological outputs through processes of verbatim mapping onto their phonological representations (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001, e.g.,). In series of experiments, Roelofs (2006) designed a task in which participants had to name pictured dice, Arabic numerals, and number words and ignore congruent and incongruent dice, digit, and number word distractors initiated at several stimulus onset asynchronies (SOAs). Digits and words affected dice naming, but the opposite wasn't the case. There was mutual interference between words and digit distractors, and the same interference was observed in digit naming trials where number words appeared as distractors. Roelofs (2006) interpreted these observations as evidence that digit naming closely resembles word naming, but it is essentially different from dice naming. Seemingly, between-notation naming experiments converge to the conclusion that Arabic notation prioritizes semantic processing, whereas verbal notations can be processed by both means, semantically and asemantically.

The apparent dual-route processing of numerical notations makes it is possible to put forward a hypothesis that besides notations, numerical context can influence the selection of processing routes as well. In case of Arabic numerals, it is cardinal, ordinal, and nominal numerical contexts that could modulate semantic/asemantic selection. This kind of conceptualization contributes to theoretical models by branching out further the types of numerical processing, adding contextual use of numbers as a factor, and brings memory systems into connection with the current models of numerical cognition. In terms of McCloskey's and Dehaene's models mentioned before, cardinal and ordinal numerical processing would imply semantic processing for the purposes of size estimation, comparison, semantic numerical relations, etc., whereas nominal numerical processing would facilitate an asemantic numerical fact retrieval, or serve as rapid transcoder between visual inputs and phonological outputs.

In order to further support the notion of nominal numerical context, we have to provide further evidence that not only number words, but Arabic numerals too, can be processed without access to their quantity. That is the main feature that distinguishes nominal from cardinal numbers. In this regard, Alameda, Cuetos, and Brysbaert (2003) used a list of 50 pairs constructed of Arabic numerals and words that are strongly associated to them (different brand names, historical events, names of media channels, e.g, boeing 747, levi's 501, Russian Revolution 1917 etc.). In the first experiment, researchers in associative priming procedure manipulated SOA, masking, and semantic relatedness between primes and targets in between-subject design. The analysis of collected naming latencies for target numerals showed increasing performance with increasing SOA, particularly for numerals that were primed by semantically related primes. This led to conclusion that strong semantic relation between word-numeral pairs can facilitate asemantic processing in naming target numerals, i.e., they could be named without appealing to magnitude processing mechanisms in the brain. However, fearing that the effect might be due to naming differences on phonological instead of semantic level, Alameda et al. (2003) proceeded with a second experiment to examine this possibility. This time they modified previous procedure by preserving only one SOA from the first experiment and they changed numerical naming task into number decision task that didn't require verbal responses. The modified version required from participants to decide whether presented target is legitimate Arabic numeral or combination of letters and digits (e.g., "Battle of Hastings — 12F9" or "World War — 1945"). The primes remained related and unrelated to the target like in previous experiment. Second experiment rejected the hypothesis that associative priming occurred on a phonological instead on a semantic level. Responses to legal numerals were faster than the illegal numerals for the condition when they were preceded by semantically associated prime. Finally, the authors concluded that neurologically healthy people are able to process Arabic numerals without any quantitative mediation.

Granted that different processing occurs for cardinal and non-cardinal numerals, it is also possible that both contexts are differently represented in memory. Hinrichs and Novick (1982) approached this question by looking at the serial position curve in recall of memorized digit series (for the original discovery of serial position effect see Stigler, 1978). The authors reasoned that nominal use of numerals requires precise representation in memory, in contrast to cardinal use that is a subject to approximation. For example, when a phone number is dialed, each digit has to be recalled precisely in order and value, opposite to prices that can be recalled as "about values" (compare "090-1234-5678" to "¥ 689,954", which approximates to "about ¥ 700,000"). Researchers wanted to know whether people differently remember numerals that are used in nominal and cardinal contexts. In series of experiments, paired associate list of four-digit car prices or last four digits of phone numbers were given to participants to remember. It was hypothesized that recollection of both types of stimuli will be different for car prices and phone numbers, since participants will tend to retain first thousands, hundreds, tens, and lastly, ones in case of cardinal prices (monotonically decreasing serial curve) in contrast to phone numbers where flat or bowed curves were expected (bimodal curve from the first and the last items in a series). Serial position curves for both kinds of stimuli were similar in the first two experimental manipulations and tended to shown decreasing order of correctly remembered items, which was consistent with the magnitude encoding hypothesis. However, an important manipulation in Experiment 3 reverted serial position curve for phone numbers to the well documented bowed shape (which was similar to situations when non-numerical items are remembered, e.g, letters). This time, participants were explicitly instructed to remember all four phone digits. Hinrichs and Novick (1982) interpreted these results in terms of dominant magnitude encoding. In other words, in the absence of explicit instructions participants tended to remember car prices and telephone numbers in a cardinal mode, but when explicitly instructed, they reverted to nominal encoding for phone digits. Peculiarly, this reversion was much weaker when car prices encoding task preceded phone numbers task, but was evident when phone numbers were remembered first. The final conclusion of the study argued for possible existence of two types of number encoding in semantic memory, with magnitude representation being the dominant mode when people remember numerals.

Given all points above, it's time to summarize the argumentation and restate the main hypothesis. Most of the research in numerical cognition addressed cardinal aspects of numbers. Yet, current debate on asemantic number processing brings non-cardinal numerical aspects back into discussion. Different numerical notations (Arabic numerals, written numbers, dots, etc.) activate particular mental representations, but there is a possibility that some notations are better at activating the analog magnitude code. Most of the research agrees on the point that Arabic notation obligatorily activates magnitude code, in contrast to verbal notations that can bypass the semantic mediation and gain direct access to phonological systems.

Despite of the increasing knowledge in the field, still it is relatively unknown how contextual information relates to numerical processing. When Arabic numerals are used in nominal contexts like postal codes, telephone numbers, social security numbers, etc., it is unclear whether they activate corresponding mental magnitude representations or they just exist as a special case in which asemantic processing is achievable. In order to address this uncertainty, priming paradigm and numerical comparison were combined into a single procedure. Priming has been often used in numerical cognition studies to investigate unconscious processing of numerical semantics (e.g., Dehaene et al., 1998; Naccache & Dehaene, 2001a, 2001b), cross-notational interactions with the postulated semantic and asemantic routes of number processing (e.g., Reynvoet et al., 2002), symbolic and non-symbolic number processing (e.g., Roggeman, Verguts, & Fias, 2007), audio-visual cross-modal number processing (e.g., Kouider & Dehaene, 2009), number-related neuroimaging studies (e.g., Notebaert, Pesenti, & Reynvoet, 2010), number comparison vs. number-fact retrieval (e.g., Campbell & Reynvoet, 2009), and so on. In order to estimate whether there is a true difference between numerical processing of Arabic numerals within cardinal and nominal contexts, it is necessary to contrast the contexts against some robust cognitive effects. In this case, the distance effect was chosen as a cognitive measure of the degree to which numerical semantics was accessed within cardinal and nominal context. The reason for this choice is manifold. The distance effect was observed in symbolic single-digit (Dehaene & Akhavein, 1995; Moyer & Landauer, 1967; Parkman, 1971) and multi-digit studies (Dehaene, 1989; Link, 1990). The effect was also observed in non-symbolic numerosities (Buckley & Gillman, 1974; Dehaene & Changeux, 1993), non-numerical physical sizes (Moyer, 1973), and it is effective across different number notations (Dehaene, Dupoux, & Mehler, 1990; Pinel et al., 1999). Additionally, monkeys and primates show distance effect (Nieder et al., 2002; Washburn & Rumbaugh, 1991) as well as human infants and children (Sekuler & Mierkiewicz, 1977; Temple & Posner, 1998).

In sum, two experiments were designed to test the processing of Arabic numerals within cardinal and nominal contexts, i.e., to look for hypothesized differences between both. Both experiments intend to measure performance in a numerical comparison task. The context differences hypothesis will be tested by analyzing numerical distance effect, which is robust cognitive measure for semantic processing in numbers.

3.1.1 Method

Participants. Twenty-three Japanese students from Kobe University participated in the experiment. Twelve were males (age M = 21.2, SD = 5.8) and 11 were females (age M = 21.1, SD = 3). Since experimental conditions required reading Arabic numerals aloud, at the start of experimental procedure each participant was asked to confirm absence of any vocal or verbal problems. All of them had normal or corrected-to-normal vision.

Postal codes (nominal set)	Prices (cardinal set)	Masks
〒134-243	¥143,214	wRpQTL
〒231-412	¥214,342	KqGpRF
〒324-143	¥341,243	NcQLWz
〒421-213	¥421,342	xBWsDQ
〒689-768	¥697,978	hXmWFg
〒796-986	¥768,986	WLuBQz
〒867-976	¥869,786	yTqGLw
〒978-687	¥976,798	KqRHnS

Table (3.1) **Stimuli set used in Experiment 3.1 on reading and contextual influences on numerical distance.**

Stimuli and procedure. Two pseudo-random sets of six-digit prices and postal codes were used as contextual primes (Table 3.1). Each set was consisted of eight primes with initial digit ranging between 1 and 9, excluding 0 and 5. Half of the time, initial digit of the primes was smaller than five, and other half it was larger than five. In addition, the relation between primes and targets was designed in a way that first digit of primes and targets both were below five in half of the trials (numerical distance between the first prime digit and targets was kept constant to two), and in other half they were on the opposite side of five (in this case, numerical distance was constant to five). To mark the appropriate context, in front of each numeral either Japanese postal symbol (〒) or Japanese yen sign (¥) was placed. Thus, the templates for postal codes and prices looked like 〒◯◯◯ − ◯◯◯ and ¥◯◯◯,◯◯◯. All stimuli were presented in white font on a black background.

Participants sat approximately 80 cm from the computer screen and took part in four blocks of trials. Depending on the block, they were instructed either to read aloud or read silently single code or price that was presented in the center of the computer screen. The design complied with 2 $\times$ 2 cross tabulation of blocks, presented in a single sequence: Read aloud/Nominal prime (RANP), Read silently/Nominal prime (RSNP), Read aloud/Cardinal prime (RACP), and Read silently/Cardinal prime (RSCP; i.e., RANP $\rightarrow$ RSNP $\rightarrow$ RACP $\rightarrow$ RSCP). Participants completed 24 practice trials in a same order as the following 192 experimental trials. Each trial started either with a postal code or a price that was replaced by two quickly inter-

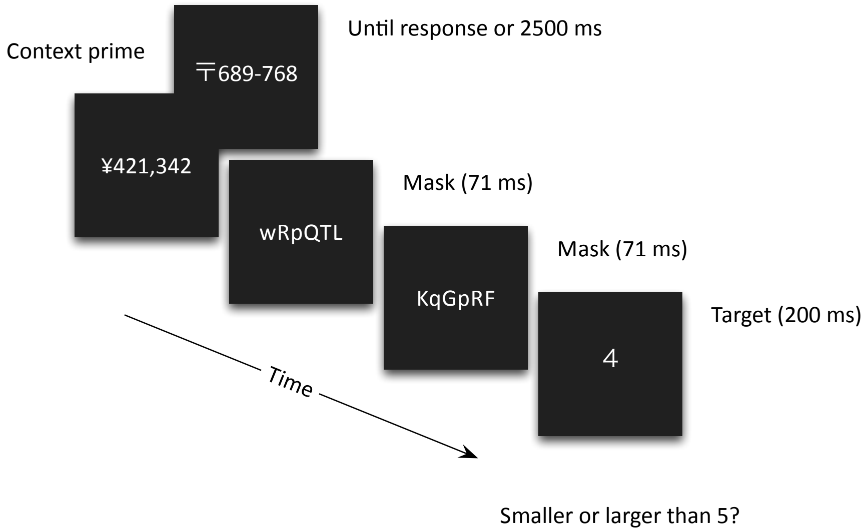

Figure (3.1) **Stimuli presentation and procedure in Experiment 3.1 on reading and contextual influences on numerical distance.** Participants were required to decide whether target numeral was larger or smaller than standard numeral five by pressing one of the designated buttons (5 never appeared as target numeral).

changing six-letter masks (71 ms each), which were followed by a target numeral in the center of the screen. The target flashed briefly for 200 ms and participants had to decide as quickly as possible whether target numeral was smaller or larger than five by pressing "S" key for small with their left, and "L" key for large with their right index finger on a standard computer keyboard. Both, speed and accuracy were emphasized. The experimental trials were randomly presented (Figure 3.1).

Read aloud conditions were self-paced and obliged participants to read aloud primes and read them adequately depending on a context. After reading them aloud, participants pressed "S" and "L" buttons at the same time and trial proceeded to its end. Postal codes required nominal reading like "postal code: one, three, four, two, four, three" for 〒134-243, while prices prompted cardinal reading (e.g., "one hundred forty-three thousand two hundred fourteen yen" for ¥143,214)*. In Read silently condition, postal codes and prices stayed onscreen for 2500 ms after which they automatically disappeared. Participants in this condition were instructed to read contextual primes covertly. Silently read primes didn't require synchronized button-press like the primes in Read aloud condition. Instead, only one button-press response

*Please note that this is an English translation since the experiment was done with Japanese participants in Japanese language.

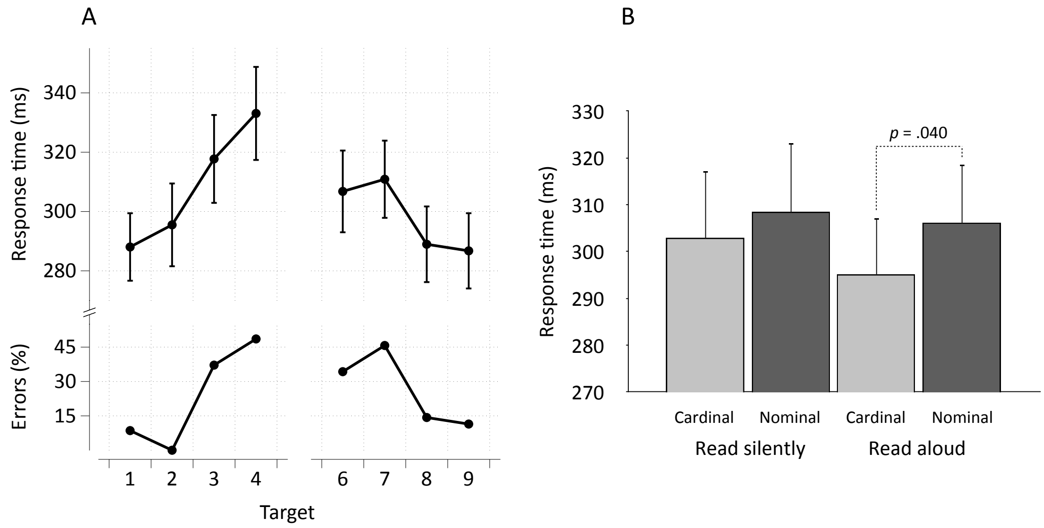

Figure (3.2) **Correct mean RTs for each experimental condition and target numeral in Experiment 3.1 on reading and contextual influences on numerical distance.** **(A)** Correct mean RTs and in the lower panel error percentages for each target separately. **(B)** Correct mean RTs for each condition. Cardinal and nominal numerical contexts differed only in read aloud condition. The error bars represent standard error of the mean.

was required for the target. Response speed and accuracy were encouraged.

3.1.2 Results

Response times between 150-1000 ms were taken into account. One male participant was excluded from the analysis because he failed to follow experimental instructions and had unusually large number of incorrect responses (> 25%). Each participant completed 192 trials (48 per block) totaling in 4224 trials for all.

Error rate was extremely low (1.7%) and didn't exceed 10% per participant. Together with the outliers, 3.3% of responses were removed leaving 4085 trials for further analysis. There was no speed accuracy trade-off, as it was indicated by the positive correlation between RTs and error percentages computed over 16 cells of the design (two contexts, two reading conditions, and four absolute distances from five): $r = 0.74, n = 16, p = .001$. Correct RTs and error percentages for each target are depicted in Figure 3.2, A. In addition, correct RTs and error percentages for each target in different context and reading conditions are depicted

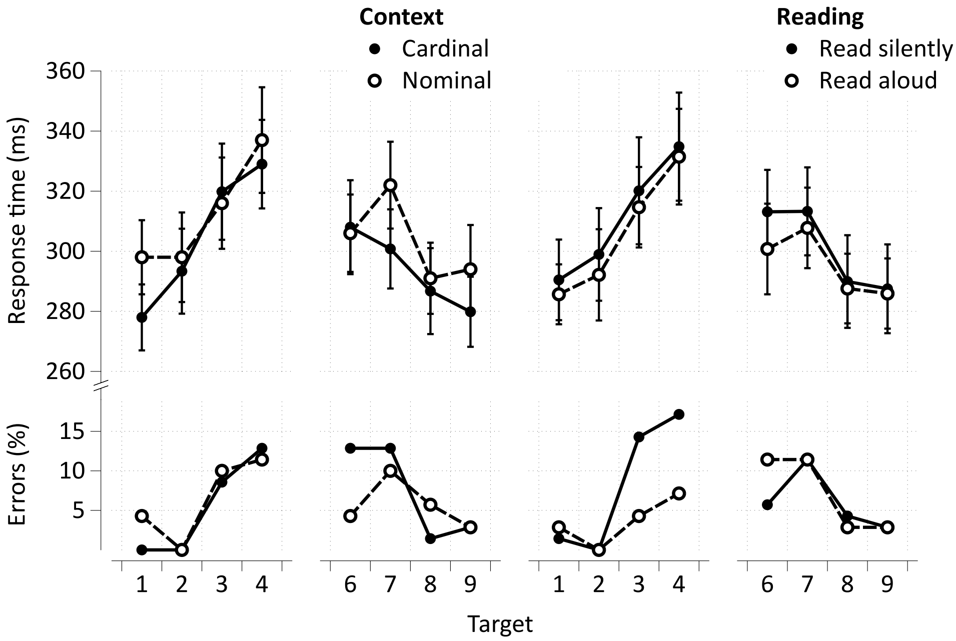

Figure (3.3) **Correct mean RTs and error percentages for targets categorized by context and reading in Experiment 3.1 on reading and contextual influences on numerical distance.** The error bars represent standard error of the mean.

in Figure 3.3. One 2 × 2 × 4 repeated measures ANOVA (Context [Cardinal, Nominal] × Reading [Read aloud, Read silently] × Absolute distance from 5 [1, 2, 3, 4]) of correct RTs revealed significant main effect for Distance $F(3,63) = 37.78, MSE = 22256, p < .001$, and a marginal main effect for Context $F(1,21) = 3.36, MSE = 6016, p = .081$. In addition the Context × Distance approached significance $F(3,63) = 2.36, MSE = 811, p = .080$. No other significant main effects or interactions were observed. The same ANOVA for error percentages pointed to one significant main effect for Distance $F(3,63) = 8.69, MSE = 4.11, p < .001$, and marginally significant Context × Reading interaction $F(1,21) = 4.11, MSE = 1.88, p = .056$. No other main effects or interactions reached alpha level of. 05.

Despite the fact that the ANOVA for correct RTs didn't reach necessary alpha level of. 05 other that for the main effect of Distance, post-hoc analyses showed significant difference of 11 ms between Read aloud/Cardinal prime and Read aloud/Nominal prime, $t(21) = -2.19, p = .040$, Figure 3.2, B. Finally, there were significant contextual differences at four absolute dis-

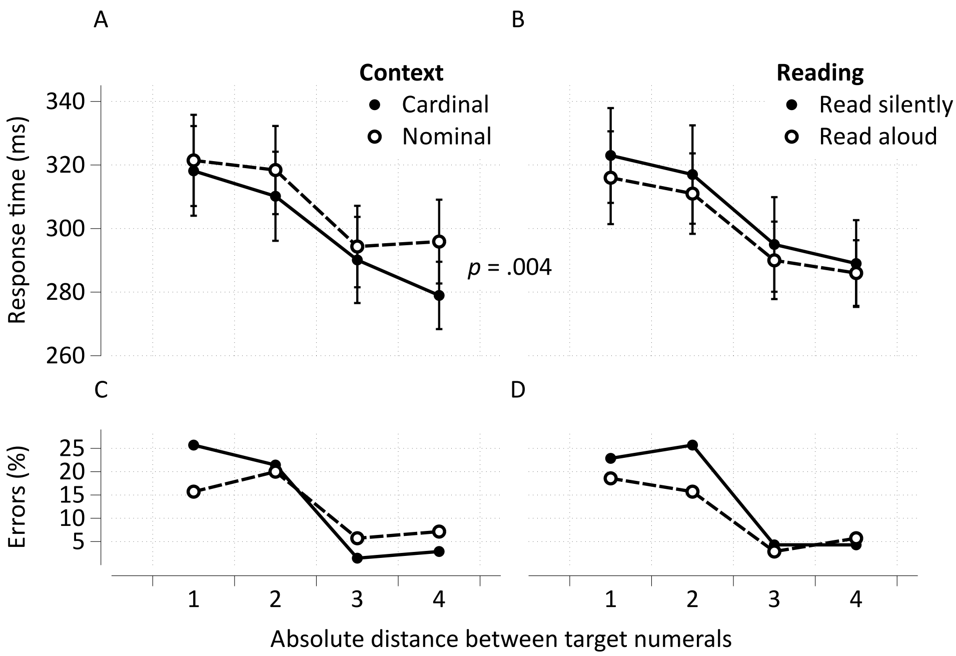

Figure (3.4) **Distance effect in Experiment 3.1 on reading and contextual influences on numerical distance.** Correct mean RTs and error percentages for context **(A, C)** and reading **(B, D)** conditions. The error bars represent standard error of the mean.

tances from 5 ($t[21] = -3.21, p = .004$; Figure 3.4, A; error percentages are shown in Figure 3.4, C). Although main effect for Reading and its interaction with Distance (Reading × Distance) were not significant, for comparison purposes RTs and error percentages for aloud and silent reading conditions are shown in Figures 3.4, B and D as a function of absolute numerical distance of targets and midpoint five.

3.1.3 Discussion

Arabic numerals are extremely reliable in conveying quantitative information. However, depending on their contextual use they can incorporate ordinal and nominal information. The flexibility of Arabic numerals is best shown in their abundant use as labels of objects, events, spaces, etc. By combining priming paradigm with the distance effect as a robust cognitive measure of numerical semantics, Experiment 3.1 aimed to look for chronometric patterns that might hint different underlying processing of numerals used in cardinal and nominal context.

Similarly, the experiment addressed the issue of possible dissociations between spoken numerals and numerals that were observed. Dual-route models like Dehaene's triple code model assume asemantic processing routes in addition to the "default" semantic routes that permit a hypothesis that some difference may be expected between both numerical contexts (Dehaene, 1992).

Contextual manipulation in Experiment 3.1 revealed dissimilar performance between prices (cardinal numerals) and postal codes (nominal numerals). When comparison-to-standard numerical task was primed by prices read silently or aloud, classical distance effect was observed. In other words, as targets deviated further from the midpoint 5, participants' classification of target numerals as smaller or larger showed decreasing latencies. However, when nominal primes were presented before the comparison task, there was a slight deviation from the classical distance effect, i.e., participants were slower to respond especially for the numerals most distant from the standard of 5 (specifically, 1 and 9). In the case of Experiment 3.1, reading aloud and reading numerical primes silently didn't seem to have an effect on the consequent numerical comparison-to-standard task.

The marginal main effect for Context and the faster overall RTs for cardinal primes over nominal ones hint apparent incongruity between nominal primes and comparison task to a certain degree. To put it differently, nominal contextual engagement possibly activates asemantic type of numerical processing that was reflected as small RT cost in the numerical comparison task. However, we need to be extremely cautious when generalizing this observation. One of the possible drawbacks in Experiment 3.1 was monosequential presentation of stimuli in which any order effects in the stimuli presentation (in case they are present) are virtually unobservable. Additionally, Experiment 3.1 provided data from a comparison task that measures numerical distance up to four absolute unites, but there are similar numerical comparison tasks that are able to provide measurements up to eight numerical distance units.

Experiment 3.2 addressed these issues and attempted to provide extensive evidence on the possible influences of spoken or silently read cardinal and nominal contextual primes on the consequent numerical comparison task.

3.2 Cardinal and nominal contextual priming in a smaller/larger numerical judgments task

The first experiment primarily showed that numerals in different contexts (postal codes and prices) indicate priming effects on the subsequent numerical comparison task. In other words, when cardinal numerals appeared prior to the comparison task, a classical distance effect was observed. Yet, magnitude irrelevant nominal primes primed larger latencies for targets that are four units away from the designated referent point of five (see Figure 3.4, A). Although contextual manipulations in the experiment influenced the comparison process to some extent, it didn't matter whether postal codes and prices were aloud or silently read. Still, the effects observed in the first experiment were rather weak and it is hard to reach general conclusions. Serious experimental research is based on cautious interpretation of findings and rigorous idea testing and therefore, second experiment was carried out in hope to confirm or disconfirm results obtained in first experiment. Although both experiments relied on same testing paradigms, there were some crucial differences.

First of all, participants in first experiment performed within single sequence of blocks in the following order: Read aloud/Nominal prime (RANP), Read silently/Nominal prime (RSNP), Read aloud/Cardinal prime (RACP), and Read silently/Cardinal prime (RSCP; i.e., RANP → RSNP → RACP → RSCP)*. Experiment two controlled for possible artifacts that could originate in presentation of single sequence by implementing four counter-balanced experimental blocks. Furthermore, first experiment allowed observations up to four absolute distances from the standard five, but it is of quintessential interest to observe the distance effect up to eight units observable in single-digit designs. This is achievable when comparison-to-standard task is replaced with smaller/larger judgments for two simultaneously presented numerals. Previous data already showed partial dissimilarities between the contextual primes at four units from the standard by favoring cardinal over nominal primes, but it was uncertain whether this trend would continue if numerical distance were measured up to eight units.

*Legend: RSCP (Read silently/Cardinal prime); RACP (Read aloud/Cardinal prime); RSNP (Read silently/Nominal prime); and RANP (Read aloud/Nominal prime).

Block sequence	Males	Females	Subtotal	
RSCP → RACP → RSNP → RANP	3	2	5	
RACP → RSCP → RANP → RSNP	3	3	6	
RSNP → RANP → RSCP → RACP	3	2	5	
RANP → RSNP → RACP → RSCP	3	4	7	Total = 23

Table (3.2) **Experiment 3.2 on reading and contextual influences on numerical distance had a counter-balanced design for the order in which separate conditions were presented.**

3.2.1 Method

Participants. Different group of twenty-two Kobe University students participated in the second experiment. Males (age M = 21.9, SD = 5.3) and females (age M = 20, SD = 1.1) were randomly assigned to one of the four experimental conditions. Five participants completed the experiment in the following block sequence: RSCP → RACP → RSNP → RANP; another six participants performed in RACP → RSCP → RANP → RSNP sequence; five participants in RSNP → RANP → RSCP → RACP; and finally six more participated in RANP → RSNP → RACP → RSCP block sequence (Table 3.2). As in experiment one, all participants confirmed absence of verbal and vocal problems. All participants had normal or corrected-to-normal vision.

Stimuli and procedure. Stimuli and procedure for Experiment 3.2 were similar to Experiment 3.1 with several important modifications. First, new stimuli set was generated in two separate blocks of random five-digit numbers including zero that were combined with 1, 4, 6, and 9 as foremost digit to form prices and postal codes for silent and aloud reading conditions (Table 3.3). One set was generated for the silent reading condition and another set for aloud reading condition. Sets within each reading condition were recycled for both contextual primes, as the same six-digit numerals were used as postal codes and prices at the same time. As in previous experiment, the generic form of stimuli followed 〒◯◯◯−◯◯◯ and ¥◯◯◯,◯◯◯ templates. Japanese postal symbol and Japanese sign for yen preceded each six-digit numeral and served as contextual markers. As previously, cardinal reading was instructed for cardinal primes, while nominal primes prompted nominal reading.

Read aloud		Read silently		
Postal codes	Prices	Postal codes	Prices	Masks
〒x92-298	¥x92,298	〒x61-198	¥x61,198	wRpQTL
〒x40-892	¥x40,892	〒x65-360	¥x65,360	KqGpRF
〒x17-876	¥x17,876	〒x77-088	¥x77,088	NcQLWz
〒x15-294	¥x15,294	〒x71-312	¥x71,312	xBWsDQ
〒x18-060	¥x18,060	〒x84-460	¥x84,460	hXmWFg
〒x31-498	¥x31,498	〒x35-087	¥x35,087	WLuBQz
〒x59-103	¥x59,103	〒x21-436	¥x21,436	yTqGLw
〒x21-091	¥x21,091	〒x82-875	¥x82,875	KqRHnS
〒x62-115	¥x62,115	〒x81-477	¥x81,477	
〒x98-484	¥x98,484	〒x69-496	¥x69,496	
〒x24-506	¥x24,506	〒x89-243	¥x89,243	
〒x99-437	¥x99,437	〒x68-404	¥x68,404	
〒x89-375	¥x89,375	〒x48-369	¥x48,369	
〒x08-660	¥x08,660	〒x79-278	¥x79,278	
〒x92-149	¥x92,149	〒x24-439	¥x24,439	
〒x63-304	¥x63,304	〒x31-589	¥x31,589	

Table (3.3) **Experiment 3.2 on reading and contextual influences on numerical distance stimuli set.**

Obviously, comparison-to-standard task from Experiment 3.1 was replaced by comparison task that required choice of the larger numeral between two simultaneously presented numerical (e.g., 3 8). The experimental design ensured all numerical distances from 1 to 8 to be equally represented in all experimental conditions. One half of larger numerals in each target pair appeared on the left, and the other half appeared on the right. For example, a postal code (e.g., 〒192-298) came before target pair 2 8, but 8 2 were preceded by a different postal code (〒162-115). Participants had to decide which numeral in the pair was larger by pressing corresponding button to the side as quickly as possible. In Experiment 3.2, responses were made with "z" and ". " keys on a standard computer keyboard, but keys' identity was concealed with two white stickers placed on the top of each key.

Each participant successfully completed 32 practice trials before the start of the experimental session. The order of the practice trials was equivalent to the particular block sequence in which participant was placed in. The experimental session contained 256 trials (64 trials per block). Just as in Experiment 3.1, depending on the block, each trial begun with either

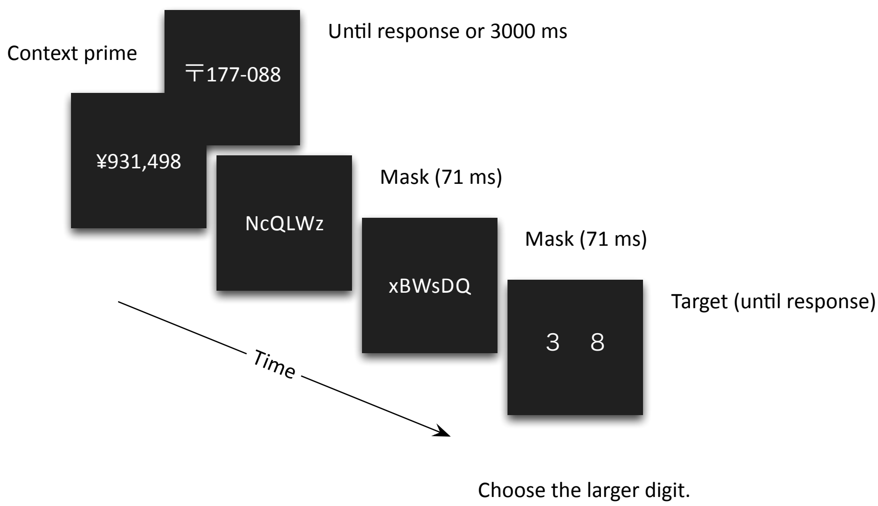

Figure (3.5) **Stimuli presentation in Experiment 3.2 on reading and contextual influences on numerical distance.** Participants compared two simultaneously presented target numerals and had to decide which one is larger by pressing corresponding buttons.

cardinal or nominal prime that was covertly or overtly read in the particular mode of reading (nominal or cardinal; e.g., "postal code — one, three, four, two, four, three" for 〒134-243 or "one hundred forty-three thousand two hundred fourteen yen" for ¥143,214)*. Read aloud primes required additional self-paced response, i.e., participant had to press simultaneously both white keys for the trial to proceed. In the case of silently read primes, there was no need for such response because primes automatically expired after 3000 ms, and therefore only one discrimination response for the larger digit was required. As soon as contextual primes disappeared from the screen, two letter masks interchanged for total of 142 ms, after which two digits appeared in the center of the screen. Target pair remained on the screen until response was made. Both, speed and accuracy were emphasized (Figure 3.5).

*The actual reading was in Japanese language.

3.2.2 Results

Response times falling between 150-1000 ms were analyzed. One female participant (RANP $\rightarrow$ RSNP $\rightarrow$ RACP $\rightarrow$ RSCP group) was excluded from the analysis because she made unusually large number of error responses ($> 15\%$). Taken together, all 22 participants completed 5632 trials, out which 5541 met analysis criteria. Errors were comparably smaller than Experiment 3.1 and accounted for negligible 1.3% of the whole data set. The outliers accounted for 0.3% and led to removal of 1.6% of total response time scores. There was no speed accuracy trade-off, as it was indicated by the positive correlation between RTs and error percentages computed over 32 cells of the design (two contexts, two reading conditions, and eight numerical distances): $r = 0.85, n = 32, p < .001$.

First of all, data were scrutinized for eventual sequence-of-blocks effect, i.e., whether groups differed between each other. One three-way $4 \times 2 \times 2$ mixed ANOVA with repeated measures on the last two factors (Group $\times$ Context [Cardinal, Nominal] $\times$ Reading [Read aloud, Read silently]) made it clear that the performance between groups didn't differ as shown by the absence of main effect for Group as well as absence of interactions between Group $\times$ Context and Group $\times$ Reading (all $p > .725$, Figure 3.6, A). Additionally, correct RTs for initial numerals in all primes (1, 4, 6, 9) were analyzed in contrast to Context, Reading, and Distance manipulation. A four-way repeated measures ANOVA, $4 \times 2 \times 2 \times 8$ (Prime [1, 4, 6, 9] $\times$ Context [Cardinal, Nominal] $\times$ Reading [Read aloud, Read silently] $\times$ Distance [1-8]) didn't show significant main effect for Prime, nor any of the Prime $\times$ Context, Prime $\times$ Reading, and Prime $\times$ Distance pointed to statistical significance (Figure 3.6, B).

The lack of differences between groups and primes gave confidence to analyze current design as it was fully within subject repeated measures design. Correct RTs were summarized into one table regardless of the group or prime and were analyzed in $2 \times 2 \times 8$ repeated measures ANOVA (Context [Cardinal, Nominal] $\times$ Reading [Read aloud, Read silently] $\times$ Distance [1-8]). Like in Experiment 3.1, there was significant main effect for Distance $F(7,147) = 58.16, MSE = 35314, p < .001$. In addition, main effect for Reading reached statistical significance $F(1,21) = 15.71, MSE = 74618, p = .001$ (Figure 3.6, C), coupled with three significant interactions between Context $\times$ Distance $F(7,147) = 3.92, MSE = 2185, p = .001$ (Figure 3.7, A), Reading $\times$ Distance $F(7,147) = 25.46, MSE = 13944, p < .001$ (Figure

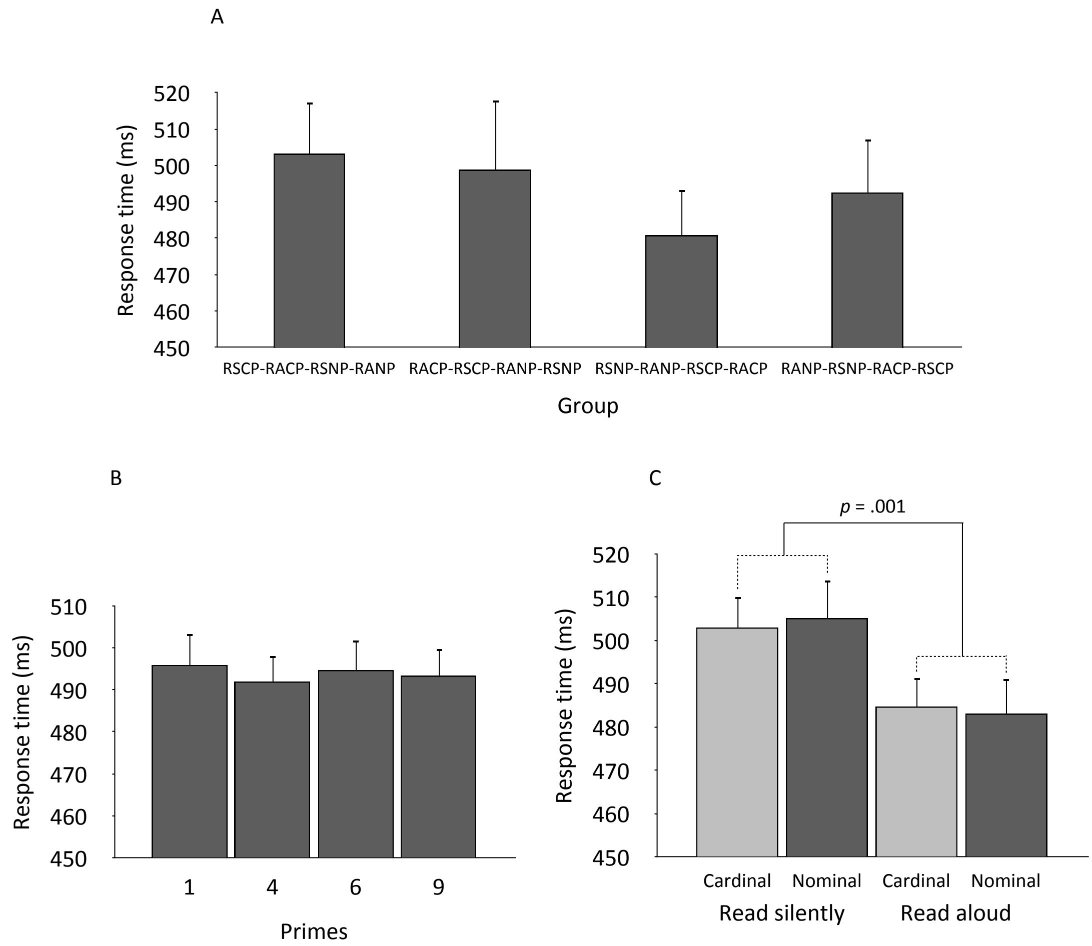

Figure (3.6) **Bar charts for correct mean RTs in Experiment 3.2 on reading and contextual influences on numerical distance. (A)** Four counter-balanced groups performing in different experimental block sequences. **(B)** Correct mean RTs for each initial digit of contextual primes. **(C)** Correct mean RTs for each condition. The error bars represent standard error of the mean.

3.7, B), and Context × Reading × Distance $F(7,147) = 3.04, MSE = 1785, p = .005$.

Furthermore, the error rate in Experiment 3.2 was very low and someone may question the necessity and validity of performing further error analyses. However, same 2 × 2 × 8 repeated measures ANOVA on error percentages pointed out to a similar pattern of statistical differences in agreement with correct RTs ANOVA. In other words, error percentages ANOVA revealed significant main effect for Distance $F(7,147) = 8.97, MSE = 2.24, p < .001$ (Figure 3.7, C and D), main effect for Reading that was approaching significance $F(1,21) = 3.16, MSE = 0.40, p = .090$, and Reading × Distance interaction $F(7,147) = 3.64, MSE = 0.97, p = .001$ (Figure 3.7, D).

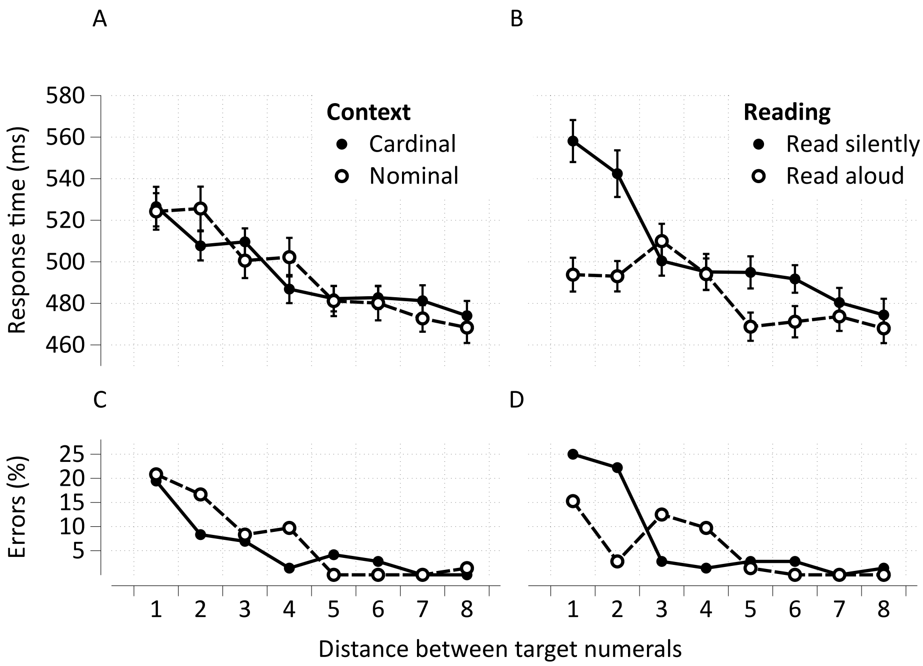

Figure (3.7) **Correct mean RTs and error percentages for Context and Reading in Experiment 3.2 on reading and contextual influences on numerical distance along full numerical distance spectrum of target numerals (1 to 8).** The error bars represent standard error of the mean.

By the same token, correct RTs were subjected to a simplified ANOVA model in order to frame more explicit general conclusions. This time, Distance factor was categorized into three levels — small, medium, and large — by pooling the mean of distances 1 and 2, 4 and 5, 7 and 8 respectively for each dimension. Thus, 2 × 2 × 8 model was reduced to 2 × 2 × 3 repeated measures ANOVA (Context [Cardinal, Nominal] × Reading [Read aloud, Read silently] × Distance [Small, Medium, Large]). The main effects for Distance and Reading were statistically significant ($F[2,42] = 127.32, MSE = 52609, p < .001$ and $F[1,21] = 21.86, MSE = 43346, p < .001$). In addition, there was a robust interaction between Context × Distance ($F[2,42] = 6.42, MSE = 1476, p = .004$, Figure 3.8, A) and between Reading × Distance ($F[2,42] = 47.25, MSE = 16235, p < .001$, Figure 3.8, B).

The 2 × 2 × 3 repeated measures ANOVA on error percentages led to similar results as the main effects for Distance and Reading reached significance ($F[2,42] = 30.94, MSE =$

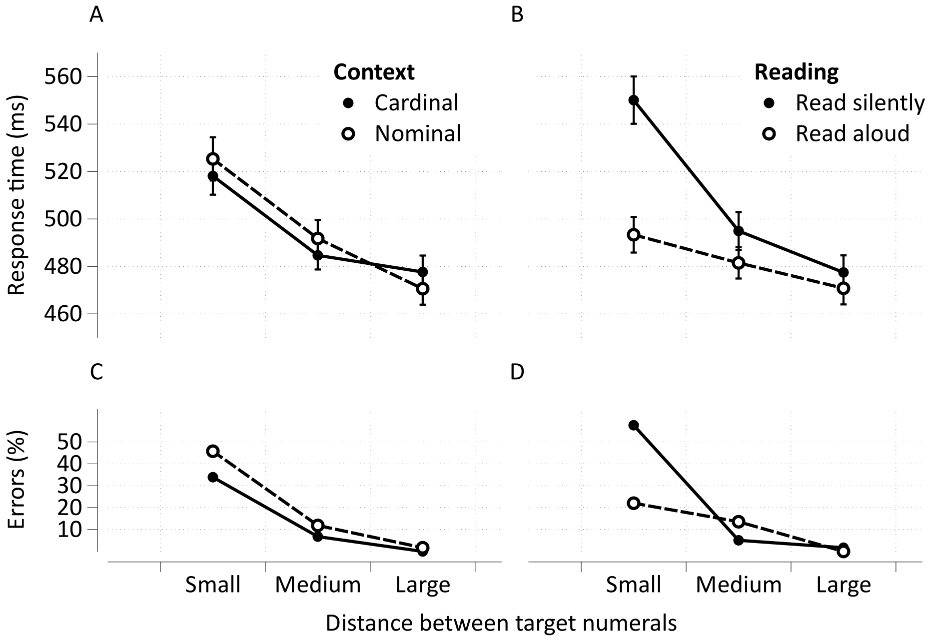

Figure (3.8) **Correct mean RTs and error percentages for Context and Reading in Experiment 3.2 on reading and contextual influences on numerical distance depicted as a function of small, medium, and large summarized numerical distances of target numerals.** The error bars represent standard error of the mean.

$19.11, p < .001$ and $F[1,21] = 5.32, MSE = 3.15, p = .031$) as well as significant interaction between Reading × Distance $F(2,42) = 9.70, MSE = 6.05, p < .001$, Figure 3.8, D) coupled with marginal significance for Context × Reading × Distance $F(2,42) = 2.99, MSE = 2.74, p = .061$. No other main effects or interactions were statistically significant.

3.2.3 Discussion

Experiment 3.2 attempted to control the possible nuisance variables originating in the order of presentation of the stimuli, and at the same time extended the scope of distance effect. Contrary to Experiment 3.1, there were no statistically significant differences between contextual primes, however there was relatively large difference between the spoken numerals and the ones that were read silently. In other words, classical distance effect disappeared when prices and postal codes were transcoded from their Arabic notation to spoken notation. Instead, small numerical distances between target pairs didn't interfere with the performance in comparison task. For example, pairs with numerical distance of 1 were processed 65 ms faster when comparison task was primed by spoken numerals than when the primes were silently read. The "flattening" of the distance effect between different reading conditions strongly suggests different processing in cases when transcoding from Arabic notation to spoken notation was required. The simplified Context [Cardinal, Nominal] $\times$ Reading [Read aloud, Read silently] $\times$ Distance [Small, Medium, Large] ANOVA model made it clear that reading aloud numerical primes affects small and medium distances, while the large distances seem to have reached a ceiling effect.

3.3 General Discussion on Experiments 3.1 and 3.2

Experiments 3.1 and 3.2 tested the hypothesis that cardinal and nominal numerical contexts coupled with verbal numerical transcoding engage separate cognitive processing mechanisms. Both experiments looked for different priming effects on the numerical comparison tasks in which Arabic numerals were read silently or transcoded to spoken numerals. By combining semantic priming paradigm and numerical comparison tasks, and by using a cognitive estimator of magnitude representation (distance effect), Experiment 3.1 provided evidence for better performance when numerical comparison task was primed by cardinal prices in contrast to nominal postal codes. In addition, different processing seems to be in effect in Experiment 3.2 when Arabic notation was transcoded to spoken words. Verbal manipulation of both contexts in Experiment 3.2 greatly affected the distance effect by making it virtually non-observable. When spoken performance wasn't required for prices and postal codes, small numerical distances between target numerals caused longer response latencies, in opposition to faster response times for target pairs with larger numerical distances between them. That is to say, a classical distance effect was observed. However, when both contextual primes were read aloud, small numerical distances of target pairs showed faster response latencies as well and this conversion from Arabic numerals to spoken number words facilitated the performance in numerical comparison task and drastically reduced the distance effect.

The distance effect is considered to be originating in the overlapping distributions of the corresponding numerical units within the mental number line (MNL; Restle, 1970). For example, it will take more time to choose the larger digit between 2 and 3 than between 2 and 8 because distributions of the first pair overlap significantly more than distributions of the second pair. As a result, two propositions for the organization of numerical units in MNL have been put forward. First one assumes linear scale with scalar variability (Brannon, Wusthoff, Gallistel, & Gibbon, 2001; Gallistel & Gelman, 2000, Figure 1.2, A), whereas second proposition suggests compressed mental number line (e.g., logarithmic scale) with constant variability in which unit distributions increasingly overlap as magnitude increases (Brysbaert, 1995; Dehaene, 1992, 2001; Dehaene & Changeux, 1993, Figure 1.2, B). Thus, when two numbers are further apart, their distributions on the number line are less likely to overlap and their signal-to-noise ratio is large, producing distinct representations that could be easily discriminated.

Moreover, both experiments attempted to collect evidence for the effect of context on the numerical processing. By comparison, numerical notations have already been extensively studied and incorporated into cognitive models for number. Some contemporary models assume at least two routes for numerical processing (Dehaene, 1992). One route leads to semantic processing of numerals and the other route bypasses it. The processing of particular numeral to great extent depends on the notation in which that numeral is expressed. Arabic notation seems to depend on the semantic route more than word numerals do (Ito & Hatta, 2003). Other researchers consider the possibility that Arabic numerals too can be processes through an asemantic means (Herrera & Macizo, 2011, 2012). However, numerical notations don't exist independently from the contextual surroundings. Context is defined as "… all of the information not in the immediate sensory signal…" and "… includes information available from the previous sensory input (the prior context) and from higher knowledge sources…" (Harley, 2008, p. 266). Arabic numerals include additional contextual information and are generally used in three contexts: cardinal, ordinal, and nominal (Nieder, 2005; Wiese, 2003). Cardinal numerals express quantities, ordinal express order, while perhaps nominal numerals don't express quantitative information because they are used in non-cardinal contexts (e.g., labels).

Inhibitory priming effect of nominal primes on the numerical comparison task in Experiment 3.1 could be explained by primes' incongruence with the task. The overlearned association between Arabic numerals and quantities they represent is the basis for the automatic activation of numerical magnitude even when an activation is not required or task irrelevant (Dehaene et al., 1993; Henik & Tzelgov, 1982). Thus non-cardinal context of the postal codes could have created artificial incongruence with the incoming number comparison task. Participants in the experiment made compulsory response to a comparison task that undoubtedly activated magnitude-discrimination response. Assumedly, the activation of mental number line could have been interrupted when nominal primes preceded it due to the additional cognitive effort needed to reconcile the incompatibility between asemantic nature of the nominal primes and semantic requirements of the task. It is important to note that conclusions on the nominal primes are drawn indirectly, from participants' performance on the consequent number comparison task. However, at this point it is not quite clear why the incongruence between nominal primes and comparison task should be evident only at four absolute distance units from the midpoint of five. It is always possible that this finding is an artifact of the monosequential design of the experimental blocks where nominal primes always were treated before cardinal primes. This kind of explanation seems to be supported by the absence of contextual differences at four distance units in Experiment 3.2. Unfortunately, in the absence of main ANOVA effects in Experiment 3.1 it is hard to reach unbiased and robust conclusion whether cardinal and nominal primes affected comparison task in two different ways, i.e., whether there were real contextual differences. Further inquiries into this issue are necessary.

On the other hand, observations in Experiment 3.2 were more straightforward. The absence of distance effect could be explained by the fact that development of linguistic competence in humans enables exact quantity extractions through the use of symbols for numbers (Carey, 2004; Gallistel & Gelman, 1992; Gordon, 2004; Le Corre & Carey, 2007; Pica et al., 2004). Spoken production of Arabic numerals require exact access to the quantity that each numeral represents. In general terms, it can be said that "digitalization" of the analog number line may be occurring when Arabic numerals are mapped onto analog number line. In this way, through the active use of linguistic number symbols, analog magnitude line transforms into a digital magnitude line, in which the analog distributions for spoken numbers are quantified as unit impulse functions (Figure 3.9, A and B; also see Nieder, 2005). Fast response latencies for small and middle numerical distances in Experiment 3.2 can be explained by the amplified

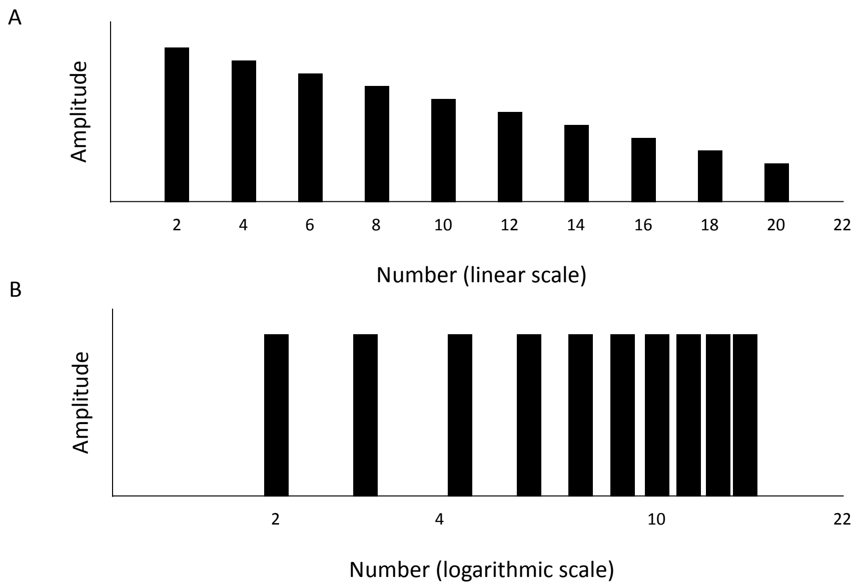

Figure (3.9) **Two propositions for the coding of "digitalized" number line in which numbers are illustrated as unit impulse functions. (A)** Illustration of the digitalized number line in accordance with linear magnitude representation models. **(B)** Illustration of the digitalized number line in accordance with logarithmic magnitude representation models.

saliency of each number unit in the digital number line, and by the increased signal-to-noise ratio since the overlapping of number distributions has been reduced. In this regard, if some form of digitalization truly occurs, we would expect to see interference between verbal number forms and other magnitude related effects (e.g., SNARC or magnitude effects; Dehaene et al., 1993).

Relatedly, Izard and Dehaene (2008) built a model in which they explain how numerical symbols are mapped onto number line, and how given number reference calibrates the performance in number estimation tasks that is a subject of great variability. The model has been studied and tested by estimating smaller and larger visual dot arrays and it assumes two number processing systems: approximate quantity system and exact systems. Non-calibrated estimations tend to underestimate the actual number in the presented array, but when estimation is calibrated by providing certain numerical references (e.g., fixed number of dots before the start of experiment), participants become far better in their estimations. To put it shortly, certain calibrating procedures can largely reduce initial noise of mental number line. Extraction of exact number meaning may be done by transforming the mental number line into, what

Izard and Dehaene (2008) call — *a response grid*. In their view, the response grid is formed when verbal labels are assigned to the segmented mental number line through certain external environment criteria and internal psychophysical rules. The grid is flexible and can be adapted for the purposes of number externalization. However, it is important to point out that verbal transcoding in Experiment 3.2 was not performed during the numerical task per se, but instead numerical primes were the ones that were read aloud or silently. That fact reveals an intimate nature between two or more Arabic numerals and their mutual dependence. When exact meaning of grouped numerals is verbally extracted in holistic or sequential manner, the analog magnitude representation transforms to a partially digitalized number line. Most important, that transformation can affect numerical processing of the consecutive numerals. Experiment 3.2 showed that digital changes in number line morphology remain stable at least for short SOAs, and facilitate tasks that explicitly require magnitude comparisons.

Furthermore, the outcomes of both experiments were obviously quite different from each other. The first experiment revealed weak contextual differences whereas strong effect of reading appeared in Experiment 3.2. At first glance, it seems that tasks in both experiments measured the same effects, but on a second glance it is critical to acknowledge few differences between comparison to a standard and comparison of simultaneously presented numerical pairs. In the first experiment participants classified targets as smaller or larger than five, which can be understood as classification procedure, in contrast to the second experiment that involved actual numerical selection (Dehaene, 1989). Although distance effect occurred in both experimental procedures, it is believed that other numerical effects like the magnitude effect and congruity effect appear only when people compare two simultaneously presented numerals but not when they compare targets to standards. The magnitude effect is observable when smaller/larger comparison is made, but numerical distance is kept constant between given numerical pair, in which performance decreases with the increasing magnitude of that pair (Parkman, 1971). Similarly, congruity effect depends on task instructions and when participants are told to select larger numeral in a pair, generally faster response times are observed for larger numerals, in contrast to when they are instructed to choose smaller numeral (Banks, Fujii, & Kayra-Stuart, 1976). In comparison-to-standard procedures like the one in Experiment 3.1, target numerals are compared to some other numeral that is held into memory. In other words, external representation is being compared to internal numerical representation (Zhang & Wang, 2005). On the other hand, two simultaneously presented numerals are entirely external and need to be internalized from their perceptual inputs into the relevant cognitive formats. Besides, available combinations of numerical pairs in comparison-to-standard tasks are far less numerous than simultaneously presented numerical pairs, a state that enables some degree of predictability and expectation. Consequently, it is plausible that standard-related procedures are less difficult to perform, and require less external-internal transcoding. This claim is supported by the faster overall response times in Experiment 3.1 in comparison to Experiment 3.2. Higher degree of external-internal translation in the second experiment could be a cause for greater linguistic activation, which on the other hand, could contribute to digitalization of the mental analog number line.

One possible limitation to the both experiments is the fact that nominal context was actually measured indirectly by observing performance on numerical comparison tasks and future experiments have to find a way to measure nominal effects in more straightforward manner. At this point it is only possible to go as far as to say that Experiment 3.1 provided few hints on cardinal and nominal numerical contexts as two different aspects of the same numerical notation. In addition, although many studies already related language to numbers, the idea of digital number line promoted and supported in the second experiment should be looked at in more detail. Learning how to digitalize analog magnitude representations could lead to extraordinary human abilities, like rapid exact estimation of large numbers not only in the subitizing range, but much above it as well. In future, this paper's analysis could be rendered more convincing with additional experimental designs in which both contextual primes will be compared in consequent non-cardinal tasks. In this way, double-dissociation with the current study can be reached. However, looking at the flexibility of numerical symbols, more studies on numbers in different contexts are necessary for complete understanding.

Altogether, Experiments 3.1 and 3.2 analyzed reading and contextual transcoding influences on the mental number line revealed through numerical distance effect. Although it should be interpreted with caution, cardinal and nominal primes had an effect on the consequent numerical comparison task in Experiment 3.1 with slight congruent advantage for cardinal over nominal primes. The most significant observation appeared in the third experiment where reading aloud Arabic numerals greatly affected distance effect by accelerating response times for small numerical distances. Thus, linguistic abilities in number comprehension and production enable humans to be both, analog and digital processors of number magnitudes.

4

Further Testing and Model of Emergent Numerical Context (Proposal for Further Research)

In the previous sections, two experiments aimed to measure the effects of numerical context expressed as prices and postal codes on the classical distance effect in a priming paradigm (sections 3.1 and 3.2). Despite the fact that clear-cut conclusions were not reached, Experiment 3.2 showed that reading contextual primes aloud significantly alters the numerical distance effect of the targets. As a consequence, numerical context may be differently represented on a conceptual and lexical level with patterns of inhibition and facilitation that depend on the levels of processing. Up to this point, the evidence is insufficient to assume that participants in the mentioned experiments processed the contextual information semantically up to the level of concepts or the findings in both experiments are due to processing only at the lexical level.

The outcome motivates reconsideration of the general approach to this issue. Following sections describe an experiment that uses semantic blocking paradigm that inspired a model of numerical context with an attempt to describe how it could emerge from a network of related and unrelated semantic concepts. The unifying feature that defines relations is the information about quantity that each concept holds. Thus, concepts that contain quantities have stronger semantic relation to each other and to Arabic numerals in addition to their mutual associations. On contrary, concepts that are related to numerals, but don't imply quantities, will be considered only associatively related to each other and to Arabic numerals omitting the semantic component.

4.1 Numerical context in a semantic blocking paradigm

In *semantic blocking paradigm* (e.g., Belke, Meyer, & Damian, 2005; Damian, Vigliocco, & Levelt, 2001; Kroll & Stewart, 1994) typically, picture and word exemplars from different semantic categories are presented in categorically homogeneous and heterogeneous blocks (Figure 4.1 and 4.7, upper panel). When asked to name pictures in a blocked condition, i.e. to name pictures that are semantically related, participants usually take longer to respond relative to the mixed condition. In contrast, words are equally named in both conditions. Traditionally, this difference is explained by the competition that occurs at the lemma level (semantic and syntactic information about concepts from the mental lexicon, without the phonological encodings for articulation; Levelt, 1992). Slower responses for pictures when they are named one after another is though to originate in the compulsory activation of their meaning, which further co-activates the meaning of other similar pictorial concepts. That is, named pictures from the same category (e.g., body parts) presented in a block, compete on a semantic level in a naming task, in contrast to words that are named without any delays since their meaning is

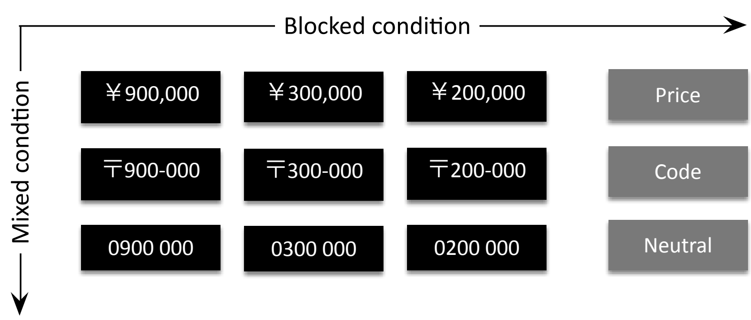

Figure (4.1) **Experimental stimuli set and semantic blocks formation.** The experiment attempted to compare the performance in a homogeneous blocks made of cardinal, neutral, or nominal stimuli to blocks consisted of mixed stimuli from each context.

not required for reading them aloud.

In the domain on numbers, Damian (2004) presented digits and number words in mixed-notation and same-notation blocks in Experiment 1 and manipulated the task for both notations in Experiment 2 (naming vs. numerical magnitude judgment). When Arabic numerals and number words were randomly intermixed within the same block, there were no significant naming latencies between both notations. However, number words showed faster naming latencies than Arabic numerals in the same-notation blocks, suggesting different naming processes between notations. In Experiment 2, task performance (naming vs. magnitude judgment) was dependent on the notational input and again, number words were named faster than digits, but digits were categorized as smaller or larger faster than number words. The author concluded that naming number words isn't different than naming other word categories, and this is accomplished through an asemantic means.

Studies that used priming procedures in which both Arabic and written notations were used as brief primes proposed that contrary to picture-word dichotomy, number naming activates both semantic and asemantic routes simultaneously, but semantic route speed is faster for Arabic numerals and asemantic for verbal ones (Reynvoet et al., 2002). More recent studies complicated the issue even further by providing evidence for Arabic numerals naming without semantic mediation. Herrera and Macizo (2011, 2012) in an adapted version of the semantic blocking paradigm observed facilitation in the blocked conditions relative to the mixed ones and also explained this observation by lack of competition at lemma level. In other words, naming of Arabic numerals is done through phonological means only, and finally the authors concluded that digits, similar to number words, might be named without access to their meaning.

The discussion on naming can be further extended into the domain of numerical context. First of all, according to the few studies described above, it seems that the process of naming numbers is somewhat neutral with ability to incline towards one mode of processing or another, and is probably dependent on the task requirements, instructions, prior exposure to stimuli, and the presence of other stimuli. Thus, naming digits looks promising as a choice of a task to measure contextual effects. Digit naming in combination with the semantic blocking paradigm allows grouping of numerical categories and control over their presentation in a homogeneous and heterogeneous manner. The main aim of the current experiment was to compare naming latencies within blocks of cardinal, neutral, and nominal numerals, to sets consisted of mixed categories combined from each context. Experiment's working hypothesis stated that when series of numbers come after another in a uniform block consisted of only one context, should generate different naming latencies compared to the same numbers grouped in a mixed block constructed of all three numerical contexts. Since the naming of digits is sensitive to the manipulation of the task that favors either semantic or asemantic processing, we should be able to observe differences between quantity-relevant and quantity-irrelevant contexts, particularly differences between the cardinal and nominal contexts if truly either of them gains access to meaning, and the other one does not. Additionally, if genuinely digits are named without access to their meaning as it was shown in Herrera and Macizo (2011), then we should observe no differences in latencies between the blocked and mixed conditions. Moreover, if latencies in response times for stimuli that are semantically close arise at the lemma level as suggested by the research on naming pictures, than any evidence for different timing patterns in naming between contexts could be tentatively taken as evidence for different lemma representations. Finally, in case numerical context has stronger influence when it is presented in a block rather than when it is presented in a mix with other contexts, we would expect to find an interaction between the context and blocking conditions.

4.1.1 Method

Participants. Ten Japanese students participated in the experiment. Five of them were males and the other five were females, all students of Kobe University (age M = 21.2, SD = 1.3 for males and 1.9 for females). Upon the arrival, they were given general information about the experiment and asked to confirm that they recognize contextual stimuli printed out on a piece of paper as a sample, without any prior suggestion by the experimenter. They recognized the three contextual stimuli as price, postal code and neutral number, after which they were asked to seat in front of a computer. The experiment complied with ABBA design and half of the participants started with blocked conditions, whereas the others with mixed. One experimental session lasted for about 30 min. All of them confirmed absence of vocal or visual defects.

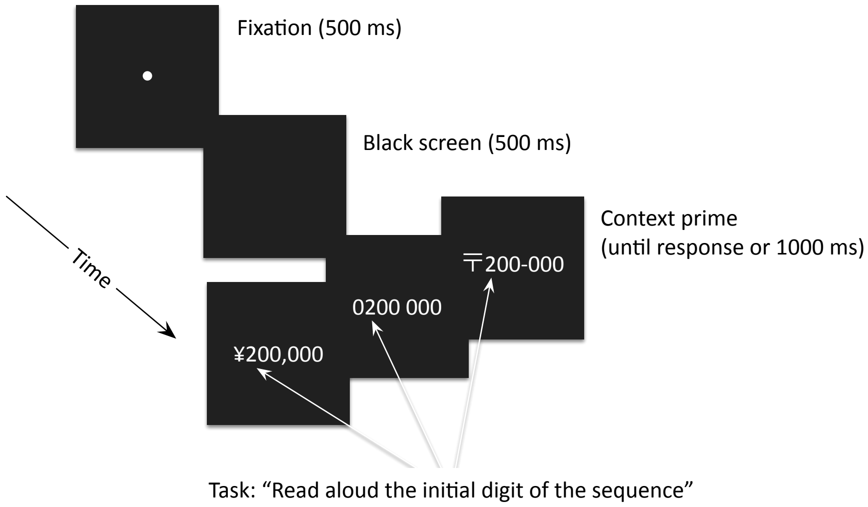

Figure (4.2) **Numerical context in a semantic blocking task flow.** Participants were required to read the initial digit of the cardinal and nominal numerals as well as the non-zero digit in the neutral context stimuli (the position of the neutral digit was always same with the positions of the initial digits from the other contexts that had either “yen” sign or a postal code in front).

Stimuli and procedure. All stimuli were presented in white color on a black computer screen. Participants made responses with a voice key triggered through a headset and the distance between participant’s head and the center of the screen was approximately 70 cm. Stimuli contained prices (cardinal set), postal codes (nominal set), and neutral numbers (neutral set). Each stimulus was eight characters long, but the first, the second, and the fifth symbol differed among contexts (see Figure 4.1). Rest of the digits found in all stimuli contained zeros. Only the digit in the second position from the left was randomly manipulated during trials. Each digit from 1 to 9 was repeated six times per context creating a total of 54 cardinal, 54 nominal, and 54 neutral number stimuli (total of 162). Same number of stimuli for each context appeared in the blocked and in the mixed conditions leading to total of 324 trials for each participant (with an addition 18 practice trials). Each trial begun with 500 ms fixation point, followed by a blank screen for another 500 ms, after which targets appeared in the center and remained until participant’s response or 1000 ms. Participants were asked to name the second digit from left as fast as possible. Their voice triggered the voice key which recorded responses from the onset of the context target until the participant’s response or 1000 ms (Figure 4.2). Since Japanese language has a peculiar feature to posses two words for 4 and 7, participants were asked to use "yon" instead of "shi" and "nana" instead of "shichi"for better acoustic discriminability. Furthermore, all responses were recorded with an external microphone for later error examination by the experimenter. Scores that were considered to be an error were removed from the dataset following all of Roelofs (2006)'s criteria, except the one on the response window period, which was lowered from 1500 ms to 1000: wrong response, wrong pronunciation, a disfluency, voice key triggered by a non-speech sound, and failure to respond within 1000 ms after target presentation.

As mentioned previously, stimuli were grouped into homogeneous blocks (e.g., cardinal numerals were presented from 1 to 9 in a random order, then nominal, then neutral, and so on), and heterogeneous blocks in which 1 to 9 were presented in a random order as well, but this time each digit was coming from different context. Based on this, two blocked and two mixed conditions were created, each containing 81 trials in random order (see Figure 4.1). During the experimental sessions there were three self-paced breaks after each homogeneous or heterogeneous block (in other words after each 81st trial).

4.1.2 Results

The analysis was performed on response times ranging between 100 and 1000 ms. Due to response failures, erroneous responses, and excluded trials in which same digits appeared twice in a row (e.g., 2 after 2), 5% of the data were removed from the analysis. The corrected dataset was subjected to 2 $\times$ 3 repeated measures ANOVA with Blocking and Context as within factors (Blocking [Blocked, Mixed] and Context [Cardinal, Neutral, Nominal]), which only revealed significant main effect for Context ($F[2,18] = 3.96$, $MSE = 210.76$, $p = .038$). Stimuli presentation in blocks did not seem to affect the outcome of the experiment seen by the absence of main effect for Blocking ($F[1,9] = 0.24$, $MSE = 63.82$, $p = .633$) and Blocking $\times$ Context interaction ($F[2,18] = 2.2$, $MSE = 93.01$, $p = .14$). A post-hoc two-tailed paired t-test revealed slightly slower naming times for postal codes in comparison to the prices ($t[9] = 2.69$, $p = .025$, see Figure 4.3).

Additional finding of interest is the presence of priming distance effect that is evident when numerically close primes facilitate target's processing in a linear fashion (e.g., den Heyer & Briand, 1986; Reynvoet et al., 2002). In other words, the closer is the prime to the target, the

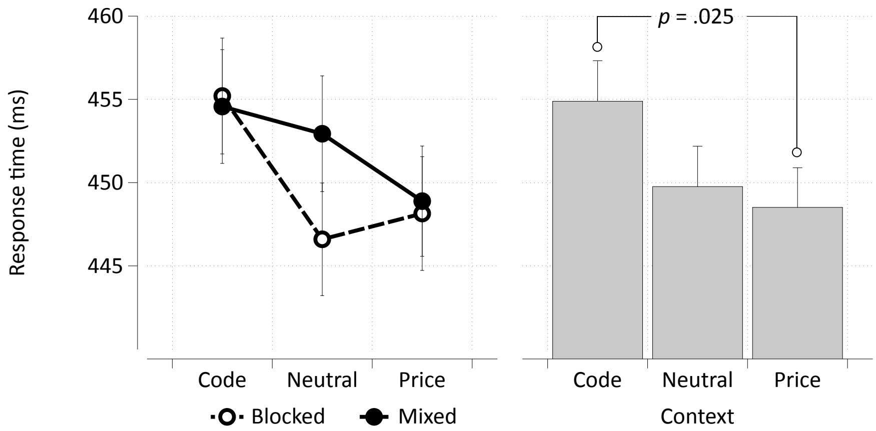

Figure (4.3) **Response times for Blocking and Context conditions in the experiment on numerical context in a semantic blocking paradigm.** Marginal main effect for Context was evident and no interaction between Blocking and Context. Post hoc paired *t*-test revealed slightly slower naming times for postal codes in comparison to the prices. Error bars represent the standard error of the mean.

faster response times are observed. To investigate the effect, another 2×8 repeated measures ANOVA was performed on the Context (Cardinal, Neutral, Nominal) as one factor, and absolute distance from previous digit (1-8) as a second factor. The analysis showed significant effect of priming distance, $F(7,63) = 4.16$, $MSE = 6523$, $p < .001$, but no interaction with the Context ($F[2,18] = 0.74$, $MSE = 1147$, $p = .492$, Figure 4.4).

Finally, this experiment was an excellent opportunity to measure the time required for native Japanese students to pronounce digits from 1 to 9. Although it is not main focus of this experiment, still it is interesting to observe that responses for digits 1 and 9 are among the slowest ones, whereas responses for 4 and 6 are among the fastest (Figure 4.5). One-way ANOVA confirms this observation and reveals this special features of the Japanese language ($F[8,72] = 6.78$, $MSE = 7433$, $p < .001$).

4.1.3 Discussion

The naming speeds of Arabic numerals presented in different contexts were measured and analyzed in a semantic blocking paradigm. A major findings are the main effect of context

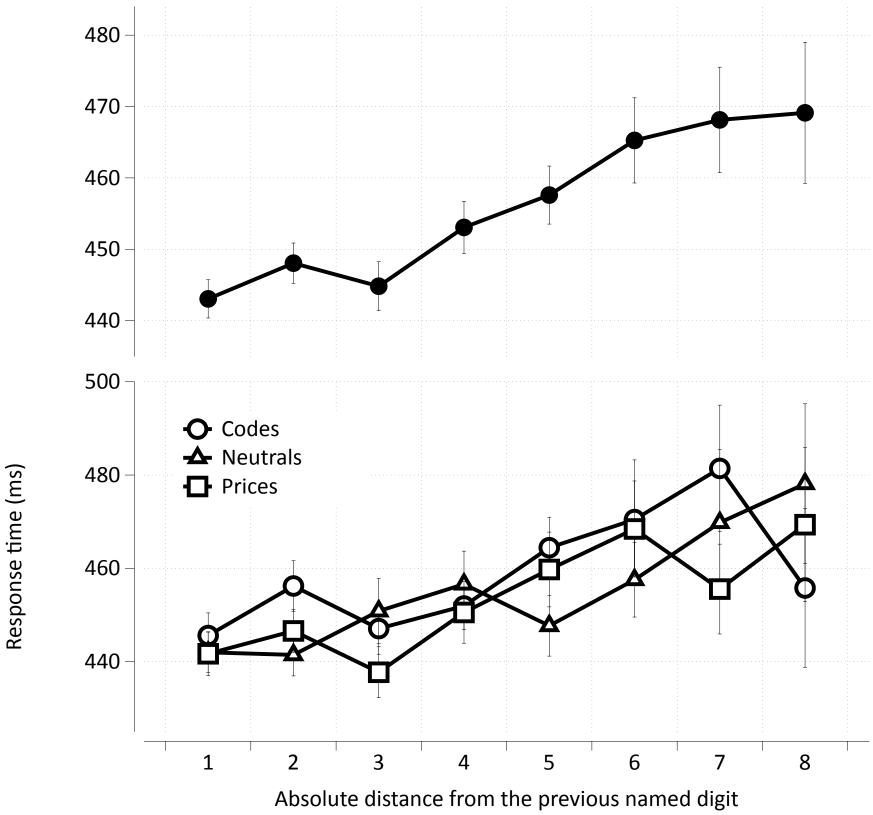

Figure (4.4) **Priming distance effect.** When a prime's numerical value is equal or close to the target's one, the performance in lexical tasks on targets is enhanced. For instance, people are faster to identify the numeral 5 if it was preceded by 4, and as the value deviates further from the target, its latencies are getting larger. Error bars represent standard error of the mean.

where digits in prices were named slightly faster that postal codes, the absence of Blocking × Context interaction, and the presence of a priming distance effect.

Numerical context appears to be immune to the blocking of the stimuli according to cardinal, neutral, and nominal classifications. It seems that the lack of interaction possibly tells us that participants did not create clear boundaries between the three hypothesized categories of number, and it seems that they were processed in a more general manner. One of the reasons for this could be the uniformity of the task, in which naming responses were made only on digits, without the addition of other pictorial or orthographic stimuli. For example, Herrera

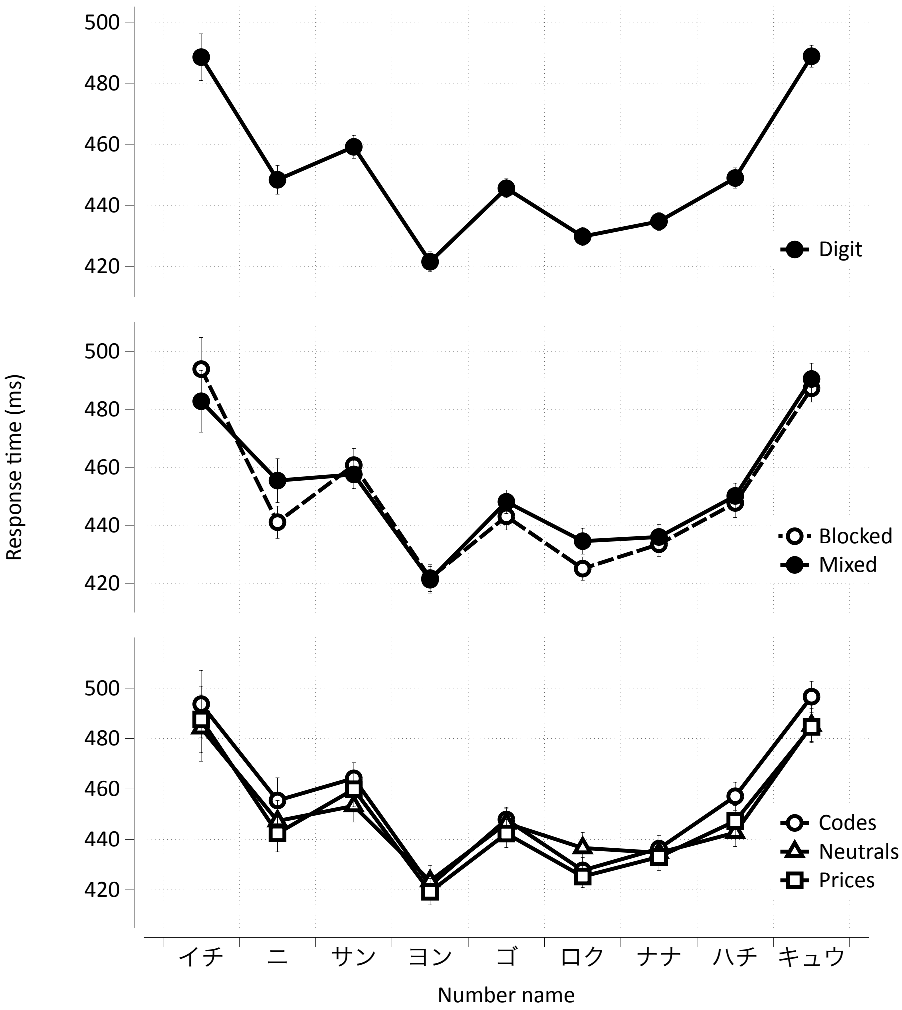

Figure (4.5) **Naming latencies for each digit.** This experiment was an excellent opportunity to measure how long it takes for native Japanese to pronounce digits form 1 to 9. As shown, a bowed line was obtained with the longest latencies for 1 and 9. The naming of each individual digit does not seem to be affected by blocking and context manipulations. Error bars represent standard error of the mean.

and Macizo (2011) compared naming times for digits to times for pictures from other categories like body parts or vehicles in a semantic blocking paradigm. Perhaps, category-switch cost is much weaker for contextual than for an clear semantic information that is readily accessible from the semantic memory and top-down knowledge. Still, the slight advantage of prices over postal codes suggests that to some extent, contextual classification indeed has occurred, although did not have enough potential to create differences between homogeneous and heterogeneous blocks of contexts. In other words, slower timing for nominal targets may be dependent on the lemma level like any other categories that require overt verbal response, but because postal codes hold vaguer information than prices in terms of quantity, the overall response latencies could be longer because of the longer de-noising processes. Another possible source of nominal inhibition could be the harder consolidation between postal marks in front and the digit that comes next. The associative nature of postal codes makes them simply harder to compile, which raises general processing time for this kind of associatively, but not semantically related concepts.

On the other hand, the observed priming distance effect shows that prior exposure to a digit modulated the naming of the current target linearly, in a pattern of faster response times for numerically closer prime-target pairs and slower for far pairs, strongly suggesting an automatic activation of numerical magnitude throughout the experiment. Also, it looks that the automaticity was overall for all digits regardless of their context as seen in the absence of interaction for contexts and distances. There is a vast support in literature for involuntary processing of semantic dimensions of Arabic number form, in quantity-judgments, calculation, number estimation tasks as well as other other tasks that do not require any quantity processing, like number-naming tasks (Ganor-Stern & Tzelgov, 2008; Henik & Tzelgov, 1982; Naparstek & Henik, 2010; Reynvoet et al., 2002). Current data support the idea of Reynvoet et al. (2002) about asymmetric dual activation of semantic and asemantic processing routes in number naming with faster and dominant semantic route for Arabic numerals and slower asemantic one for written ones.

In short, current experiment provided evidence for different naming times between digits in postal codes and prices. The difference was rather small, but the paradigm was able to detect it. Slower responses for codes may be due to the weaker nature of nominal numerical context, which was overpowered by the strong cardinal properties of prices that automatically activated their magnitudes, creating a global priming distance effect. However, the absence of blocking effects is still puzzling, but one possible explanation for this observation is the uniform naming of digits that ultimately came from the same cognitive category. Hypothetically, adding pictorial stimuli from different categories may restore blocking effects as observed in Herrera and Macizo (2011). Most important, current data suggest that the asematic naming of digits is still quite uncertain possibility and certainly, further research on that issue is necessary.

4.2 Proposal for model of emerging numerical context

In spite of the fact that researchers classify Arabic numerals as cardinal, ordinal, and nominal (Nieder, 2005; Wiese, 2003), it remains unclear how numerical context arises on a cognitive level, and little has been elaborated on this issue in the previous sections. Semantic blocking experiment and other experiments in this thesis, gave a notion of how contextual information may have an effect on numbers. With this in mind, the issue has to be re-approached with a proposal of a model that describes how numerical context could emerge from a network of number and number-related concepts. A good starting point to approach this issue is one early theory of human semantic processing named *spreading-activation theory* proposed by Collins and Loftus (1975). The authors suggested that cognitive concepts are represented as associated nodes on a network that vary in the degree of association strength. Due to their proximity, connections between nearby nodes are stronger and as a result, the information flow is enhanced between these particular nodes. A single node becomes activated when it receives enough input signal from the connected nodes and its activation threshold has been reached. As soon as a node activates, the activation propagates further to other connected nodes that have not been activated by the initial input. However, as activation spreads in the network, it loses its initial energy and the longer it travels, the weaker it becomes. That is, semantically distant nodes will affect each other less due to the dissipation of the activation spread between them (den Heyer & Briand, 1986). Furthermore, Collins and Loftus (1975) explain that a particular node fires not only when it receives strong input signal from the nearby nodes, but it also becomes active when far-away nodes send weak sub-threshold signals that eventually accumulate and reach the necessary activation threshold. Spreading-activation theory has been successful in explaining a wide range of cognitive phenomena including semantic and associative priming, category discrimination, memory retrieval, etc. When it comes to retrieving memories, another important factor in the notion of spreading activation is the so-called *fan effect* or the number of associated facts with a particular concept (Anderson, 1974; Anderson

& Reder, 1999). The effect is usually demonstrated when people are asked to commit pieces of information to memory and later tested to identify correct sentences from foil sentences constructed from the remembered material. The occurrence of the effects suggest that concepts and their related counterparts are organized into memory as chunks of related and mutually associated pieces of information.

Building upon this and other accounts, many contemporary cognitive models accept the idea that activating a node in the network leads to activation of other nodes as well. However, in contrast to the spreading activation that propagates serially from node to node, more recent models, particularly the ones that focus on language production, assume parallel activation of cohorts of nodes instead (e.g., swinging lexical network; Rahman & Melinger, 2009). These models clearly distinguish between concepts that are associatively related from concepts that fall within the same semantic categories. For illustration, a pair of concepts like ‘hand’ and ‘finger’ can be semantically related and come from the same category (body parts) or pairs like ‘hand’ and ‘soap’ can be associatively related, but come from different semantic categories. One property that relatively quickly emerges from the pair ‘hand’ and ‘finger’ is the additional information about the related super-category (i.e., body parts), but this is not immediately apparent in ‘hand’ and ’soap’ pair. In other words, the implicit information in the first pair can be considered as a form of a context, which guides further categorization and possibly biases the consequential mental processes. Models that predict synchronously activated conceptual cohorts give opportunity for speculating about additional activation of “meta-cohorts” or several collections of semantically related concepts activated at the same time. With this idea in mind, it is possible to propose a model of numerical context, in which quantity-(ir)relevant contextual information arises from simultaneously activated and semantically related concepts.

A proposal of such model is given in Figure 4.6 where several subordinate quantity-relevant and quantity-irrelevant concepts are mutually co-activated giving rise to a contextual information that could possibly bias the processing of Arabic numerals category in either semantic or asemantic direction. In addition, the distinction between quantity-relevant/irrelevant cohorts is further amplified since concepts like COIN, MONEY, EXPENSIVE, PRICE, etc. are not only semantically connected to the cardinal aspects, but they very often involve ordinal information, whereas STREET, TELEPHONE, ROOM, POSTAL CODE, etc., hypothetically

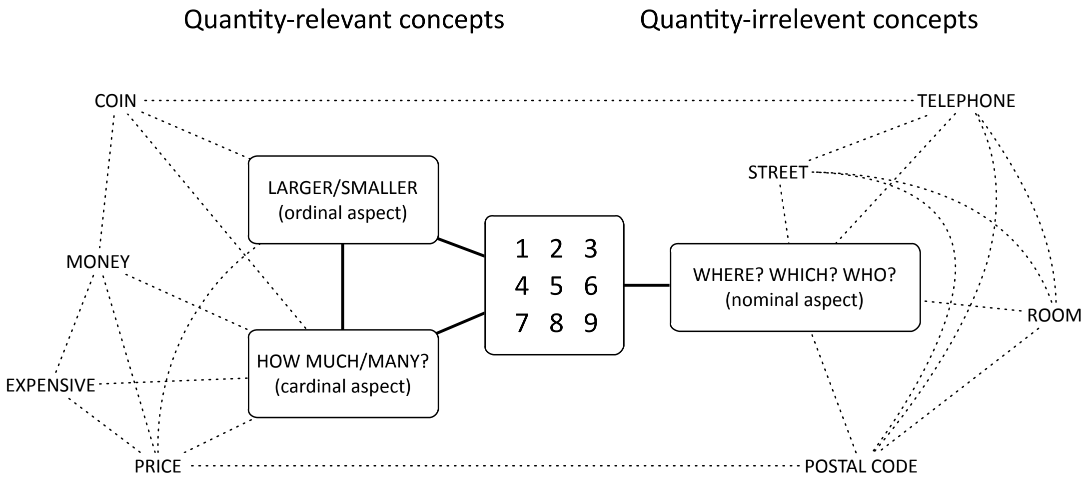

Figure (4.6) **Model of emerging numerical context.** Semantically related concepts to quantity that are activated at the same time (COIN, MONEY, EXPENSIVE, PRICE, etc.) hold an additional contextual information that could bias the processing of Arabic numerals towards quantity. On the other hand, concepts that are connected through association, but not semantics, would not (STREET, TELEPHONE, ROOM, POSTAL CODE, etc.).

solely convey nominal information.

4.2.1 Premises

Before proceeding any further, several propositions have to be given in advance about the properties of the paradigm that will enable us to test numerical context.

1. **The testing paradigm should be able to generate context environments.** Very often it is a challenge for the experimenter to control the effect of sensory information that is not immediately accessible to us, but present in the nearby environment. The priming effects of context are repeatedly seen in social, cognitive, perceptual, and other domains of human mental life. For illustration, researchers in the field of social psychology have shown that the unconscious environmental cues have profound influence on how people judge other people. Williams and Bargh (2008) found that even brief cold or warm tactile sensation of which participants were unaware, biases their judgments of other people towards "colder" or "warmer" personalities. Likewise, cognitive psychologists Nisbett and T. D. Wilson (1977) asked male psychology students to memorize a list of word pairs like "ocean-moon", and asked them later to freely recall detergent name. The students that were exposed to such word pairs were more likely to report "Tide" as

detergent name, than the ones who had not seen "ocean-moon" pair previously. More important, when students who remembered the pair were asked about the reason why they chose "Tide", almost all never made connection between the remembered pair and their answer. In other words, although the priming effect was evident, they failed to recognize the effect of word pairs on their naming choice. Perhaps the most elegant example of controlled context comes from the memory research and *DRM paradigm* in which list of words is read to participants who are later asked to recall as many words as possible from that list. Deese (1959) in the late sixties and Roediger and McDermott (1995) few decades later, reported an interesting phenomenon of induced false recollection of words that have not been a part of previously attended lists. For example, when participants heard list like *table, sit, legs, seat, soft, desk, arm, sofa, wood, kushin, rest,* and *stool*, many of them confidently recollected *chair* although it was never mentioned in the original list. These findings indicate that people do not remember lists plainly, but to some extent they recognize sort of supra-category to which listed words belong and intrusions from words like *chair* occur because they are part of the same supra-category. These and other examples show that contextual information is constructive and has a potential to induce context-dependent behavior in people.

2. **Participants should not be able to realize that numerical context has been purposefully organized.** Since context was defined as a collection of environmental or internal cues that are somehow related to a particular task or a mental process, but at the same time are not immediately accessible to the consciousness, any experimental procedure must abide to this definition. The ideal setting would be able to provide the proper context for the desired semantic manipulation of numerals, but at the same time should not be obvious or distracting to the participant. The whole testing concept relies on the assumption that Arabic numerals have long-lasting priming relationship with cardinal, ordinal, and nominal contexts. However, this categorization should not be suggestive in a way that will create sort of an "ad-hoc" categories (Barsalou, 1983). In an attempt to make sense of the overwhelming incoming information and to succeed in accomplishing certain tasks, people often create categories "on the spot" as in "things to bring on a fishing", which include objects and actions from various natural categories. Testing

procedure should make sure that such phenomenon is not produced, and alternatively should favor natural categorization of numbers.

3. **The testing paradigm should allow control over the frequency and power of the manipulated numerical contexts.** It may be the case that contexts are not equally frequent in reality. It seems that the primary function and benefit of numerals lies in their ability to express quantities, and their syntactic flexibility makes calculating quantities possible. Consequently, it is reasonable to assume that cardinal and ordinal numerical contexts prevail over the nominal and their cardinality promotes semantic processing rather than asemantic. Indeed, models like Dehaene's triple-code suggest direct conversion between digital inputs and outputs or an asemantic route in which visual information is directed to its phonological output (Dehaene, 1992). Also, it is possible that one of the routes is weaker or slower which makes contextual processing asymmetric, and this is expected and suggested in the triple-code model that assumes faster semantic and slower asemantic route. Thus, current experimental paradigm has to be flexible enough to allow adjustments of frequency and power for each context separately.

4.2.2 Methodology and discussion

After the elaboration of the model for emerging numerical context and defining the premises for its testing, we have to identify the available paradigms that are reliable for the present purposes. For example, Herrera and Macizo (2011) made use of the semantic blocking paradigm to investigate the hotly debated issue of whether Arabic numerals in their symbolic form are named with or without access to their numerical magnitudes. In the first experiment of the study, they made five lists of semantically related categories (vehicles, furniture, animals, body-parts, and Arabic numerals) and participants had to name the elements from the lists in categorically-blocked and categorically-mixed conditions. The results from the four non-numerical picture categories did not cause any surprises and were in line with already documented findings in the literature where pictures categories are named slower when presented in a homogeneous blocks relative to when they are mixed with other categories. However, the blocked presentation of Arabic numerals not only did not affect the response times, but even

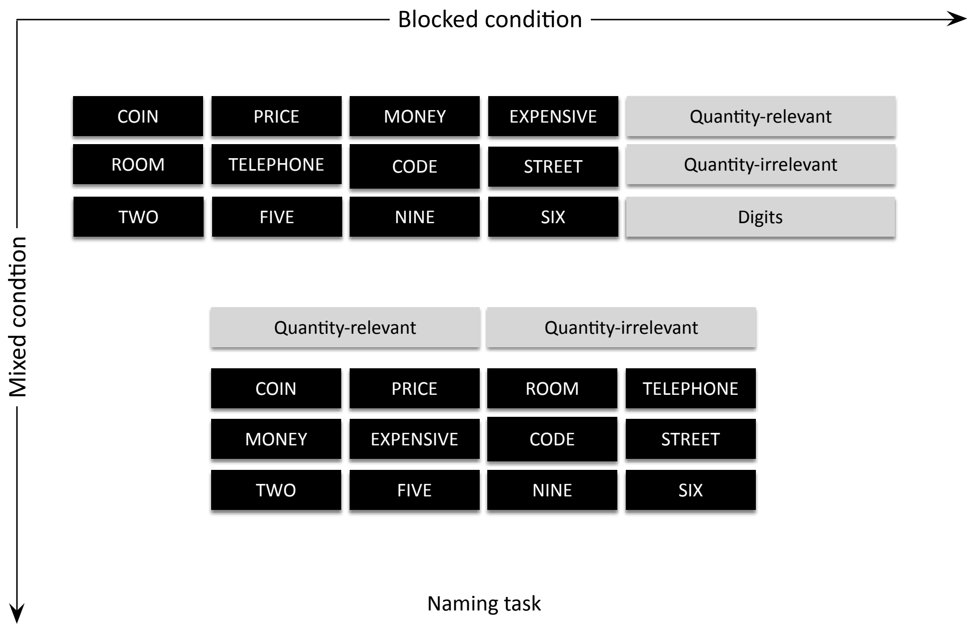

Figure (4.7) **Testing of the model of emerging numerical context involves semantic blocking of contexts.** The experiment aims to measure the effects of quantity-relevant and quantity-irrelevant mixed blocks on the digit naming (although words are depicted in the illustration, pictures of the corresponding concepts are actually planned to be used).

in some cases it showed a facilitation effect over the mixed presentation. These results were interpreted in terms of an asemantic naming of Arabic numerals.

Nevertheless, Herrera and Macizo (2011) used categories that are noticeably different from the numerical category. For the purpose of testing the model of emerging numerical context, perhaps categories in the blocking paradigm should be consisted of quantity-relevant and quantity irrelevant elements like shown in Figure 4.7. The first category would contain pictures and words exemplars like COIN, MONEY, EXPENSIVE, and PRICE which although belong to wider semantic category, create a quantity-relevant context. On the other hand, words and pictures like STREET, TELEPHONE, ROOM, CODE do not involve quantity per se. Thus, it would be effective to compare latencies between heterogeneous blocks consisted of quantity-relevant concepts and quantity-irrelevant concepts intermixed with digits.

In sum, if the proposed model realistically describes the architecture of the numerical context, then hypothetically we should be able to observe different naming latencies for quantity-relevant and quantity-irrelevant heterogenous conditions for the numerical category.

5

General Conclusion

Estimation of the environmental magnitudes is an essence of existence. In order to survive, almost every living organism has to be able to estimate light luminance, distances to objects, sound pitch, position in space, and countless other types of magnitudes that come from outside and inside of the living organisms. The invention of the advanced numeric systems confirms the importance of the magnitude estimation. Through the usage of the numeric symbols as codes for magnitude, humanity became able to estimate different properties of the environment to such an extent and accuracy like never before. Number knowledge is fundamental to daily functioning. It is hard to imagine a world without numbers, or even worse, a world in which organisms are unable to understand numerosity. Humans have no difficulties in rapid extraction of precise numeric meaning for small sets (subitizing), but as sets become larger, precision decreases and people tend to approximate (enumeration). This is true for both, symbolic and non-symbolic numerosities. Most of the time we encounter symbolic numerals usually expressed in Hindu-Arabic notations (e.g., 2, 4, 7, etc.), but different cultures have developed their own symbolic systems that are interchangeably used (e.g., in China and Japan numbers can be written as kanji).

Symbolic numerals are particularly flexible and can be used in variety of contexts. They can symbolize cardinality, rank (order), or name (label), and therefore, depending on the context are categorized as cardinal, ordinal, and nominal. Numerals in cardinal context denote total sum (magnitude) of collection of items, regardless of their quality. On the other hand, ordinal numerals emphasize single item in a set or sequence, and convey its position in relation to the other members of that set. Finally, numerals in nominal context are used as labels to designate objects and events, and seemingly have no direct relation to the numeric magnitude. Naturally, psychologists and neuroscientists are interested in how digital and non-digital magnitudes are mentally represented, and how are they perceptually and cognitively processed. One of the most significant findings in the field of numeric cognition is the fact that numeric information is represented spatially by the brain. The first serious insight into this issue was made with the observation of SNARC effect (Spatial-Numerical Association of Response Codes) according to which people are faster to respond behaviorally to small numbers with a response code on their left and for large numbers with a response code on the right. SNARC effect assumes a mental number line with left-to-right ascending orientation. Regardless of task requirements, even in cases when no magnitude judgment is required, it seems that numbers automatically activate their magnitude codes, mapped on the mental number line with their magnitude as ordering factor. However SNARC seems to be a part of more general effect called SQUARC (Spatial-Quantity Associations of Response Codes). Experiment on spatial mapping of pitch and loudness in this thesis didn't provide sufficient evidence for SQUARC effect and it is hard to reach conclusion. However, some data trends suggest cross-modal relation between magnitudes which could be spatially organized. Further inquiries on the issue are necessary.

Furthermore, almost all of the previous research focuses on cardinal and ordinal numeric contexts, yet somehow nominal context has been overlooked. Three experiments in this thesis focused on finding answers whether nominal numbers are devoid of any magnitude information, and what kinds of mechanisms operate between contextual exchanges in the usage of numerals. Other studies have shown that numeric meaning (magnitude) is rapidly and automatically accessed, and this type of semantic processing occurs even subliminally, regardless of the numeric notation. Furthermore, evidence from memory research puts forward magnitude encoding as dominant encoding, especially in cases where certain degree of ambiguity is introduced in the system. Thus, nominal numeric context may be more complicated as initially thought, with elaborate processing stages, in which numeric magnitude information has to be striped of and inhibited, while labeling information maintained. Results in Experiment 3.1 partially support the hypothesis that there is difference between processing on cardinal and nominal numbers. Cardinal primes facilitated performance on the consequent numerical comparison task, while nominal numerals did not. Although the effects were statistically weak, still we can conclude that research in contextual differences is promising and more experiments are needed in future. On the other hand, Experiment 3.2 on reading and contextual influences on numerical distance yielded to most interesting findings. When both types of primes were read aloud, performance on the numerical comparison task showed almost no distance effect. This can be explained by the hypothesis that language helps extraction of precise numerical meaning, i.e., noisy analog mental magnitudes are converted to digital and the analog number line changes to digital. The Experiment 4, similar to 3.1, provided evidence that although the same Arabic symbol is named, there are differences on a contextual level between nominal and cardinal numerals.

In summary, although experimentation on spatial mappings of pitch and loudness gave no statistically significant results, still we can say general data trends behaved hypothesis-wise, i.e., small pitch and loudness are mapped on the left and large ones on the right. Better designed and controlled experiments are necessary for definitive answer on this issue. On the other hand, experiments on reading and contextual influences on mental number line gave much better preview in the effects of context and language on the processing of Arabic numerals. In other words, cardinal and nominal numerals seem to be processed differently judging on the different performance on the consequent number comparison task. Finally, observations in Experiments 3.1 and 3.2 gave permission to hypothesize about digital number line elicited through the use of language. Experiment 4 provided evidence for simultaneous activation of numerical semantic and asemantic processes for nominal numerical contexts, of which asemantic ones are slower and much more delicate. Finally, a model of an emerging numerical context has been proposed with hope to inspire further research and contribute to our understanding of numbers.

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5. Kirjakovski, A., & Matsumoto, E. (2013). *Numerical comparison in cardinal and nominal contexts during overt and covert reading.* Manuscript submitted for publication.

(2) 国内学会／研究会における発表

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2. Kirjakovski, A., & Matsumoto, E. (2012, July). *Numeric magnitude processing within nominal and cardinal numeric contexts.* Presented at 21st Meeting of the Society for Kansai Young Experimental Psychologists, Osaka, Japan. 関西若手実験心理学研究会第21回研究会.

3. Kirjakovski, A., & Matsumoto, E. (2012, November). *One number, many contexts: Contextual numeric priming reveals differences between nominal and cardinal numerals.* Presented at the 31st Annual Meeting of the Japanese Psychonomic Society, Fukuoka, Japan. 日本基礎心理学会第31回大会.

(3) 国際会議／学会における発表

1. Kirjakovski, A. (2011, November). *Spatial shifts of the covert attention cued by symbols of non-digital nature: Possible SQUARC effect.* Presented at the 19th Annual Conference of Object, Perception, Attention, & Memory, Seattle, WA.

2. Kirjakovski, A. (2011, December). *Mental representation of numerical and non-numerical magnitudes: Insights from the SNARC and SQUARC effects.* Presented at the IBRO School of Advanced Theoretical and Computational Neurosciences, Cape Town, South Africa.

3. Kirjakovski, A., & Matsumoto, E. (2012, December). *Verbal and contextual influences on mental number line.* Presented at the IBRO-UNESCO Inter-Regional School on Computational & Theoretical Neuroscience, Hyderabad, India.

4. Kirjakovski, A., & Matsumoto, E. (2013, August). *Contextual and verbal influences on number representation.* Presented at the 18th Meeting of the European Society for Cognitive Psychology (ESCOP), Budapest, Hungary.

(4) 受賞等

1. Invitation for further research at École Polytechnique Fédérale de Lausanne (EPFL; Swiss Federal Institute of Technology in Lausanne). Award received at the IBRO School of Advanced Theoretical and Computational Neurosciences in 2011, Cape Town, South Africa. (In addition to the award, elected as class co-president.)