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Head of Institute: Prof. Dr. Dr. Markus Raab

Numbers and Force:

The sensorimotor grounding and embodiment of magnitudes

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by

Alexej Michirev

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Numbers and Force

First reviewer: Prof. Dr. Dr. Markus Raab

Second reviewer: Prof. Dr. Martin H. Fischer

Chair of the doctoral committee: Prof. Dr. Mario Thevis

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Affidavits following §7 section 2 No. 4 and 5 of the doctoral regulations from the German Sport University Cologne, February 20th 2013:

Hereby I declare:

The work presented in this thesis is the original work of the author except where acknowledged in the text. This material has not been submitted either in whole or in part for a degree at this or any other institution. Those parts or single sentences, which have been taken verbatim from other sources, are identified as citations.

I further declare that I complied with the actual "guidelines of qualified scientific work" of the German Sport University Cologne.

Date, Signature

Numbers and Force

Abstract

Magnitudes are often highly correlated in natural environments. Compared to a small stone, a larger stone of the same type is often wider, occupies more space, and weighs more. When we decide to drop the larger stone it will fall faster, produce more noise during the fall, and also crash harder on the ground than the smaller stone. When we interact with such an object, we also accumulate knowledge about this object. In the first part of this thesis, I theorize how exactly we might accumulate such knowledge and whether our body itself could have contributed to the learning processes. I also attempt to bridge how the physical interactions with continuous magnitudes as size and space might shape the learning of number size and spatial order.

In the second part of this thesis, I present four studies across which we empirically tested how numbers affected motor behavior in and outside spatial conditions. During the first two studies, we decided to measure motor behavior as passive force recordings. In the first experiment we neither found an effect of numbers on motor behavior nor how motor behavior in spatial conditions affected the production of numbers. In the second study, we found how numbers are directly coupled with motor behavior and how smaller numbers induced smaller motor magnitudes compared to larger numbers.

In the next two studies, we decided to extend the findings of the first two studies by measuring motor behavior as active responses. In study 3A we found no effect of numbers on motor magnitudes. In study 3B we found an interaction of numbers and spatial responses in which responses for smaller numbers produced smaller motor magnitudes in the left space and larger motor magnitudes in the right space compared to larger numbers. In the discussion, I connect these results to theory and argue for different mechanisms in how we represent different magnitudes.

Altogether, this dissertation adds to theoretical development by connecting and pointing out differences between different theoretical approaches. It also adds to methodological development as I describe a novel method on how to capture the processing of magnitudes. I further attempt to quantify and specify the found effects and connect them to the general field. Finally, I specify the limitations of the research project and describe practical relevance for the scientific field.

Zusammenfassung

In der Natur sind die Größenverhältnisse oft stark korreliert. Im Vergleich zu einem kleinen Stein ist ein größerer Stein der gleichen Art oft breiter, nimmt mehr Platz ein und wiegt mehr. Wenn wir beschließen, den größeren Stein fallen zu lassen, wird er schneller fallen, beim Fall mehr Geräusche verursachen und auch härter auf den Boden aufschlagen als der kleinere Stein. Wenn wir mit einem solchen Objekt interagieren, sammeln wir auch Wissen über dieses Objekt. Im ersten Teil dieser Arbeit stelle ich Theorien darüber auf, wie genau wir dieses Wissen anhäufen und ob unser Körper selbst zu den Lernprozessen beigetragen haben könnte. Ich versuche auch eine Brücke zu schlagen, wie die körperlichen Interaktionen mit konkreten Größen wie Größe und Raum das Lernen von Zahlengröße und räumlicher Ordnung prägen könnten.

Im zweiten Teil dieser Arbeit stelle ich vier Studien vor, in denen wir empirisch getestet haben, wie Zahlen das motorische Verhalten innerhalb und außerhalb räumlicher Bedingungen beeinflussen. Bei den ersten beiden Studien entschieden wir uns, das motorische Verhalten in Form von passiven Kraftaufzeichnungen zu messen. Im ersten Experiment fanden wir weder eine Auswirkung von Zahlen auf das motorische Verhalten, noch wie sich das motorische Verhalten unter räumlichen Bedingungen auf die Produktion von Zahlen auswirkte. In der zweiten Studie fanden wir heraus, dass Zahlen direkt mit dem motorischen Verhalten gekoppelt sind und dass kleinere Zahlen im Vergleich zu größeren Zahlen kleinere motorische Ausmaße hervorrufen.

In den nächsten beiden Studien beschlossen wir, die Ergebnisse der ersten beiden Studien zu erweitern, indem wir das motorische Verhalten als aktive Reaktionen maßen. In Studie 3A fanden wir keine Auswirkung der Zahlen auf die motorischen Ausmaße. In Studie 3B fanden wir eine Wechselwirkung zwischen Zahlen und räumlichen Antworten, wobei Antworten für kleinere Zahlen im Vergleich zu größeren Zahlen kleinere motorische Größen

im linken Raum und größere motorische Größen im rechten Raum erzeugten. In der Diskussion verbinde ich diese Ergebnisse mit der Theorie und argumentiere für unterschiedliche Mechanismen, wie wir unterschiedliche Größenordnungen repräsentieren.

Insgesamt trägt diese Dissertation zur theoretischen Entwicklung bei, indem sie verschiedene theoretische Ansätze miteinander verbindet und Unterschiede zwischen ihnen aufzeigt. Sie trägt auch zur methodischen Entwicklung bei, da ich eine neuartige Methode beschreibe, wie die Verarbeitung von Größenordnungen erfasst werden kann. Außerdem versuche ich, die gefundenen Effekte zu quantifizieren und zu spezifizieren und sie mit dem allgemeinen Feld zu verbinden. Schließlich nenne ich die Limitationen des Forschungsprojekts und beschreibe die praktische Relevanz für den wissenschaftlichen Bereich.

Table of Contents

List of Articles

This dissertation contains a theoretical article and an empirical study that both have been published in scientific and peer-reviewed journals. An additional empirical study is currently submitted to a journal. I am the first author of all three articles in which I also share the first authorship with a co-author in the two empirical studies. An additional empirical study was conducted but no manuscript exists so far. The published/submitted articles are kept in their published/submitted formatting and thus alter from the general outline of the thesis including reference style, reference list, and page numbers. The manuscripts of the three included articles are attached separately as Appendix 1, 2, and 3. In the thesis, Article 1 should be read in Chapter 2, Study 1 in Chapter 6, and Study 2 in Chapter 7.

Article 1

Appendix 1

Michirev, A., Musculus, L., & Raab, M. (2021). A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices. *Frontiers in Psychology, 12*, 3261. https://doi.org/10.3389/fpsyg.2021.694750

Study 1

Appendix 2

Michirev, A., Kühne, K., Lindemann, O., Fischer, M. H., & Raab, M. (2023). How to not induce SNAs: The insufficiency of directional force. *PLoS ONE 18*(6): e0288038. https://doi.org/10.1371/journal.pone.0288038

Study 2

Appendix 3

Numbers and Force

Michirev, A., Lindemann, O., Kühne, K., Fischer, M.H., & Raab, M. (submitted). Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces.

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List of Acronyms

ATOM – A Theory of Magnitude

GMS – Generalized Magnitude System

FoNARC – Force Numerical Associations of Response Codes

SNARC – Spatial Numerical Associations of Response Codes

SNAs – Spatial Numerical Associations

Acknowledgment

In real life, sometimes I struggle to express my gratitude. Here, I take the chance to compensate for the missed opportunities.

All of the persons that I mention, all of you contributed to this moment. I am here and I am writing this because you are present in my life. It would not have been possible without the sum of you all. I am writing to express my heartfelt gratitude and deep appreciation for the unwavering support, guidance, and encouragement throughout my academic and personal journey. Your contributions have been instrumental in shaping my professional and personal growth, and I truly appreciate each and every one of you.

Markus, I would like to extend my sincerest appreciation for placing your trust in me. Your general supervision and your advice guided me through complex situations and helped me make sound *choices*. I am grateful for the opportunities you have provided and the confidence you have shown in my abilities. Thank you for giving me this opportunity.

Martin, I am immensely thankful for your constant availability and willingness to provide feedback in such detail. I deeply appreciate your openness and your inviting nature. At the very beginning of my doctorate, you and your team welcomed me to your graduate school and gave me *space* to grow as an academic and a person. Thank you for being part of my journey.

Oliver, I am incredibly fortunate to have had you as a mentor. Your guidance and encouragement have been pivotal in my *academic emancipation*. Your valuable insights and advice have inspired me to push my limits in the persuasion of my own interests. I am grateful for your continued support and belief in my potential.

Katharina, I would like to express my deepest gratitude for your hands-on assistance and prompt responses to my urgent questions throughout the duration of the entire project. I am glad that *randomness* decided to pair us during this project.

Lisa, it was a chance and, if taken, the chance becomes an opportunity. I am thankful that we both had the chance and we both decided to take it. The result was the *development* of a wonderful collegial relationship that, I like to think, became a friendship. Thank you for taking that chance.

I am deeply grateful to the members of the Performance Psychology Department for their support in helping me perform. From the moment I joined, you extended a warm welcome. I am grateful to all of you who have supported me with advice and hands-on help whenever I needed it most. I am grateful to all the Ph.D. students as we all shared similar highs and lows and yet, managed to grab an occasional pizza and establish "Dönerstag" as the most delicious day. Your support has meant the world to me. Overall, I am grateful to the entire department for its inclusive culture. I appreciate the opportunity of getting to know all of you which has been and continues to be a wonderful experience.

To all my friends outside the academic bubble, thank you for believing in me and providing me with a comforting place to escape when I need it most. Many of you I have known for decades; may it continue for many more.

To my dear family, you shaped who I am today. Through you, I learned how to be persistent. Huge thanks to you, Valentin. Thank you for being the supportive brother that you are.

Melanie, einfach Danke für alles!

Project Overview and Aims

My Thesis is the result of a collaborative project based on empirical work and all manuscripts are a group effort as indicated by the authorships. For clarifying and acknowledging intellectual property, when I describe findings based on these manuscripts, I will refer to them as “our work” that “we” did. At the same time, I have provided the first and main drafts for Article 1, Studies 1, and 2. Currently, no draft for Studies 3A and 3B exists so I integrated them into this Thesis within Chapter 8. Therefore, Chapter 8 is not a draft of a stand-alone manuscript, but rather part of our experimental strategy extending Studies 1 and 2. Finally, the Thesis itself was written solely by me. When I make an interpretation beyond the involvement of my co-authors I will refer to myself as well.

This Thesis is structured in two major parts: Theoretical and empirical work. Chapters 1-3 include the theoretical introduction as Part I of this Thesis. The theoretical part aims to answer the question of *why* a “smart thing like number” (Walsh, 2015, p. 552) is found in a brain area associated with motor processing. To provide possible answers to this question, I chose the embodied cognition framework (Barsalou, 2008; M. H. Fischer, 2012; Raab & Araújo, 2019) that highlights the role of the sensorimotor system in knowledge contribution and cognition. At the same time, the embodied cognition framework challenges the prominent cognitive paradigm that rejects any influences of the sensorimotor system on cognition (e.g., Fodor, 1975).

Part I includes the first published manuscript which is referred to as Article 1. In Article 1, we reviewed the literature to gather evidence for the embodied nature of numerical cognition. For this, we integrated the embodiment with a developmental perspective to theorize how children learn and progress in their numerical knowledge. In particular, we focused on the sensorimotor experiences of finger and hand use and discussed the mechanisms that might enable fingers to contribute to the embodiment of numbers. I end the theoretical part of this Thesis in Chapter 3 in which I discuss Article 1 by finding commonalities with, but also contrasting the embodied cognition framework from A Theory of Magnitude (Walsh, 2003, 2015). This approach allowed specifying concrete predictions for the empirical part of this Thesis.

Part II of this Thesis is subdivided into Chapters 4-10 including an overview of the state of the art, the experimental strategy of the overall project, our own empirical work, and a general discussion. This empirical work strives to answer the question of how the processing of numbers can affect motor behavior. In Chapter 4.1 I describe the state of the art of the empirical work and also introduce the methodology that we used for our own empirical work for Studies 1, 2, 3A, and 3B (Chapter 4.2). The introduced methodology is important to this Thesis as it represents a novel approach from what we find in the typical state of the art experiments. The aims of the Studies are summarized in Table 1 beneath and are the following:

Study 1 tested whether numerical magnitudes affected motor magnitudes in interaction with spatial conditions. Additionally, we tested the bi-directionality between spatial conditions and numerical magnitudes.

Study 2 tested a direct coupling of numerical magnitudes and motor magnitudes. Specifically, we asked if visually processed semantic numerical magnitudes affect motor magnitudes.

Studies 3A and 3B were conducted to systematically test a direct coupling between number magnitude and motor magnitudes in and without an interaction with spatial responses.

As for a final disclaimer, I do not report the exploratory research questions from Study 1 as it does not fit into the context of this Thesis.

Table 1. Project Overview

Part I: Theoretical Work		**Aim**	
Article 1	Michirev, A., Musculus, L., & Raab, M. (2021). A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices*. Frontiers in Psychology, 12*, 3261. doi.org/10.3389/fpsyg.2021.694750	This is a theory paper aiming to provide a developmental view on the embodiment of numerical cognition.	
Part II: Empirical Work		**Aims of the research questions**	**Theoretical focus**
Study 1	Michirev, A., Kühne, K., Lindemann, O., Fischer, M. H., & Raab, M. (2023). How to not induce SNAs: The insufficiency of directional force. *PLoS ONE 18*(6): e0288038. https://doi.org/10.1371/journal.pone.0288038	Does random number generation affect motor magnitudes? Does directional force production affect random number generation?	ATOM test. Embodied bi-directionality test: from motor to concept.
Study 2	Michirev, A., Lindemann, O., Kühne, K., Fischer, M.H., & Raab, M. (submitted). Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing:	Does semantic numerical magnitude processing affect motor magnitudes?	ATOM test.

	Larger Numbers Elicit Larger Forces		
Study 3A	Unpublished https://osf.io/hdraq/?view_only=34ed2b6e50ba41429c2667d9b269c58f	Does semantic numerical magnitude processing affect motor magnitudes during active responses?	ATOM test.
Study 3B	This experiment was conducted by our cooperation partners at the University of Potsdam by Prof. Dr. Martin H. Fischer and Katharina Kühne. https://osf.io/8yb4k/?view_only=f1e8a32ff32a4880bebcbecc2def92c5	Does semantic numerical magnitude processing affect motor magnitudes during active and spatial responses?	ATOM test with spatial interactions.

Part I: Theoretical Work

Chapter 1: Theoretical Introduction

1.1 A Theory of Magnitude

This dissertation is largely inspired by the problem of "… what a smart thing like number is doing in a region of the human cortex associated with automatic and motoric processing of which we are seldom aware..." (Walsh, 2015, p. 552). One of the reasons why Walsh regards this as problematic is the modular approach that tries to localize specific functions in specific brain areas. According to that logic, there would be a "motor area" and there would be a "number area". Having both functions represented within one area is a difficult task to explain for such modular approaches. Including this problem, Walsh formulated A Theory of Magnitude (ATOM; Walsh, 2003, 2015) proposing a common metric of *action* linking three distinct modules of time, space, and quantity. In the Thesis, I took the inspiration that numbers and actions seem to be somehow intertwined and investigated *why* this might be, *how* this becomes, and *what* it means.

The above-presented quote is part of ATOM's aim to integrate three disciplines from three separate streams of literature focusing on the perception of time, space, and quantity (Walsh, 2003, 2015). According to ATOM, this integration is useful because the perception of time, space, and quantities is processed by one Generalized Magnitude System (GMS). The GMS operates from birth and processes within-magnitude dimensions such as time, space, and quantity that are prothetic (Stevens, 1957) and experienced as "more than" and "less than". An increase in one of such within-magnitude dimensions is often automatically accompanied by an increase in other within-magnitude dimensions. For example, when an object is larger it is often also more heavy than a smaller object, it falls faster, produces more noise during the fall, and also crashes harder on the ground. Magnitudes that are processed by the GMS are defined as approximate representations of continuous magnitudes along prothetic (Stevens, 1957) dimensions (Leibovich et al., 2017; Rinaldi & Girelli, 2017; Sixtus et al., 2023).

Empirical evidence for the association between within-magnitude dimensions includes the size congruency effects (Banks & Flora, 1977). The major conclusion of such size congruency effects is how difficult it is to ignore task-irrelevant size information that is presented visually. For example, when participants are asked to compare two numbers based on the physical size they are presented in, the semantic magnitude of these numbers interferes with the comparison of the physical size (Henik & Tzelgov, 1982). Therefore, the visually manipulated physical size and the semantic magnitude of a number are not independent. The authors interpreted their finding as a parallel processing mechanism between the physical and semantic size. Such parallel processing is in line with the common processing mechanism such as the GMS proposed by ATOM described above. Moreover, such effects are also found for other within-magnitude dimension including the physical size (Henik & Tzelgov, 1982), conceptual size (Gabay et al., 2013), luminance (Kadosh & Henik, 2006), line length (Dormal & Pesenti, 2007, 2009), duration (Dormal et al., 2008), dot sizes (Gebuis et al., 2009), weight (Charpentier, 1891), and others.

Critically, ATOM is not the only theory capable to explain and predict the above described effects. Other theories as the polarity correspondence (Proctor & Cho, 2006; Proctor & Xiong, 2015) or the verbal-spatial coding account (Gevers et al., 2010; Gevers, Verguts, et al., 2006) can explain such effects based on stimulus-response compatibilities. According to the polarity correspondence account, concepts are coded in polar opposites and dichotomous pairs such as “small vs. large”, “bright vs. dim”, and “heavy vs. light” (Proctor & Cho, 2006; Proctor & Xiong, 2015). These poles are either expressed in positive or negative polarity (e.g., small/minus vs. large/plus). Additionally, many experiments also utilize left and right responses (Macnamara et al., 2018) that also receive a polarity (left/minus vs. right/plus). The compatibility of stimulus and responses is then decided based on these polarities. Whenever the polarities of stimulus and response match the response is facilitated and whenever they mismatch the response is delayed. The verbal-spatial coding account operates under similar assumptions; however, the compatibilities do not exist based on structural similarities between dimensions but rather learned labels. Critically, such dichotomous pairs do not describe associations between prothetic (Stevens, 1957) within-magnitude dimensions but rather classify them in metathetic and qualitative dimensions. For instance, November is not more than February, therefore describing a metathetic and qualitative difference (see Casasanto & Pitt, 2019). Yet, they have associations with the dimension of space in which February is placed to the left of November (Gevers et al., 2003). Such dichotomous associations can also be considered as one major weakness of these two described accounts as they assume symmetrical effects across these metathetic dimensions. For instance, when the stimulus is “small vs. large” and the responses are either on “left vs. right”, “up vs. down”, or “near vs. far space”, then the congruency effects between the axes should highly correlate. However, this is not the case (Aleotti et al., 2020). In contrast, ATOM assumes symmetrical effects only very early during development (Walsh, 2015). As soon as children start interacting with the environment their sensorimotor experiences with the environment start shaping the GMS. As a result, the GMS becomes asymmetrical because the learning history with the within-magnitude dimensions is not symmetrical. The asymmetry further becomes more prominent when children start learning their language (Walsh, 2015).

Overall, the common processing mechanism of the within-magnitude dimensions is the GMS. While the GMS is thought to operate from birth, Walsh also argues that it is shaped by sensorimotor interactions with the environment. Therefore, the idea behind

ATOM is elegant in its simplicity. The common processing of the GMS of the within-magnitude dimensions has one purpose: to serve and guide perception and action. In turn, perception and action shape and develop the GMS. To quote Walsh: “space, quantity and time are linked by a common metric for action” (Walsh, 2003, p. 484).

This view is supported by congruency effects that extend to actions such as an association of higher numerical magnitudes and “larger actions”. Hereby, higher numbers induce these larger actions resulting in power grips (Lindemann et al., 2007), hand openings (Andres et al., 2004), larger gestures (Woodin et al., 2020), and harder response forces (Krause et al., 2019) as opposed to lower numerical magnitudes inducing precision grips, hand closures, smaller gestures, and softer response forces. Overall, ATOM predicts a common processing mechanism in the GMS that operates from birth. At the same time, ATOM acknowledges the relevancy of actions and suggests that they shape and develop the GMS through interactions with the environment.

1.2 The Embodied Cognition Framework

The pivotal role of actions and the sensorimotor system in shaping conceptual representations including the within-magnitude dimensions as proposed by ATOM (Walsh, 2003, 2015) is in line with the embodied cognition framework (Barsalou, 2008; M. H. Fischer & Zwaan, 2008; Matheson & Barsalou, 2018; Raab, 2021). Within the embodied cognition framework, cognition and actions are not separated and also include the conceptual representation of within-magnitude dimensions. Rather, cognition and actions are bi-directionally linked in which one provides feedback to the other. Hereby, an action is not just an output but also communicates back and provides an input. According to the embodied cognition framework, cognition is grounded in our sensorimotor system and sensorimotor experiences. The grounding of conceptual knowledge in concrete sensorimotor experiences is a strong feature that defines the embodied cognition framework. It means that the sensorimotor system will contribute to the acquisition of conceptual knowledge and will be simulated upon that knowledge retrieval (but see Muraki et al., 2023). This is also true for numerical cognition (M. H. Fischer, 2012; Lindemann & Fischer, 2015). Therefore, cognition governs actions while actions provide bottom-up feedback that is integrated and then utilized.

Crucially, ATOM (Walsh, 2003, 2015) by itself is not a theory that falls under the embodied cognition framework. Simultaneously, ATOM benefits from the specifications provided by the embodied cognition framework on how not only actions but general sensorimotor experiences can help shape conceptual knowledge. For a “smart thing like number” (Walsh, 2015, p. 552), the bi-directional relation becomes evident during concept-motor interactions between numbers and actions. For instance, Shaki and Fischer (2014) showed that generating random numbers affects turning decisions during walking. The authors reported that generating a small number is more likely to lead to a left turn while generating a larger number is more likely to lead to a right turn. The same is true for the opposite direction of concept-motor interactions. The intention to take a left turn is more likely to lead to a generation of a small number while a right turn is more likely to lead to a generation of a large number.

In conclusion, the bi-directionality assumption can provide a plausible answer to the question of why a “smart thing like a number” (Walsh, 2015, p. 552) is in a brain region associated with motor processing. It is because sensorimotor experiences “put” the number in there through interactions with numbers in numerical contexts. Overall, I use ATOM (Walsh, 2003, 2015) and the embodied cognition framework (Barsalou, 2008; M. H. Fischer & Zwaan, 2008; Matheson & Barsalou, 2018; Raab, 2021) to make specific predictions in formulating the hypotheses of the empirical research of this Thesis. Moreover, while ATOM and embodied cognition framework go hand in hand, I combine both while also trying to disentangle their individual contributions in later Chapters.

1.3 Specific Actions Lead to Specific Concepts of Numerical Cognition

The embodied cognition framework in general (Barsalou, 2008; M. H. Fischer & Zwaan, 2008; Matheson & Barsalou, 2018; Raab, 2021) and ATOM in particular (Walsh, 2003, 2015) emphasize the important role of actions for conceptual understanding including the understanding of magnitudes. However, ATOM is rather vague in specifying which actions will lead to the understanding of magnitudes. The embodied cognition framework suggests that it is the specific sensorimotor experience during the acquisition of that conceptual knowledge that is relevant. For instance, precision grip actions have the purpose of manipulating smaller objects while power grip actions manipulate larger objects. These can be also interpreted as “small or large” actions that also occupy “less or more” visual space. Therefore, actions of different sizes interacting with objects of different properties such as size and weight develop the GMS and ground these magnitudes in visual and motor magnitudes (Sixtus et al., 2023). To represent these magnitudes in modern life, we rely on number words and symbols that are abstract and precise representations of these magnitudes. Stunning for pure cognitivism but derived from the theoretical tenets of the embodied cognition framework, certain actions such as the use of fingers can help acquire numerical information including but not limited to semantic magnitude knowledge (Sixtus et al., 2023). This is especially true during development when associations are first acquired and movement matters most in knowledge acquisition (Musculus et al., 2021). In Article 1 we theorized how manual actions such as finger counting and gesturing help acquire semantic numerical understanding during development taking the embodied cognition perspective. For instance, children can learn counting principles (Gelman & Gallistel, 1978) by using their fingers (Butterworth, 1999). Finger pointing can contribute to the one-to-one correspondence principle by pointing with one finger to one object. Eventually, the child will understand that one of its fingers can represent one object in the environment. Fingers can also be used for counting and learning ordinal and cardinal information (Butterworth, 1999). Ordinality is discrete and defined as the understanding of objects' position within sequences and does not necessarily carry magnitude information. Cardinality is also discrete and defined as the understanding of the total size of sets and that the last object within a set also concludes it (Gelman & Gallistel, 1978; Sixtus et al., 2023). Therefore, the procedural use of fingers and hands during numerical knowledge acquisition can help develop conceptual understanding (U. Fischer et al., 2018).

Overall, manual actions such as pointing, finger counting, and gesturing can help shape numerical cognition that contributes to the semantic meaning of magnitude, ordinality, and cardinality. A "smart thing like number" (Walsh, 2015, p. 552) that conveys precise magnitude meaning is likely an "older and wiser magnitude" that is less precise but is linked to a number word, and symbol through actions and sensorimotor experiences in numerical contexts acquired during development.

Chapter 2: Article 1

2.1. A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices

Published as:

Michirev, A., Musculus, L., & Raab, M. (2021). A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices. *Frontiers in Psychology, 12*, https://doi.org/10.3389/fpsyg.2021.694750

Abstract:

The goal of this paper is to explore how an embodied view can redirect our understanding of decision making. To achieve this goal, we contribute a developmental embodied choice perspective. Our perspective integrates embodiment and bounded rationality from a developmental view in which the body provides cues that are used in abstract choices. Hereby, the cues evolve with the body that is not static and changes through development. To demonstrate the body's involvement in abstract choices, we will consider choices in numerical settings in which the body is not necessarily needed for the solution. For this, we consider the magnitude-judgment task in which one has to choose the larger of two magnitudes. In a nutshell, our perspective will pinpoint how the concept of embodied choices can explain the development of numerical choices.

Chapter 3: Discussion and Theoretical Extension of Article 1

3.1 Grounded and Embodied Cognition

In Article 1, we combined the developmental with the embodied cognition perspective to better understand how finger use and the related mechanisms contribute to the acquisition of numerical knowledge and semantic concepts of ordinality and cardinality (Butterworth, 1999; Gelman & Gallistel, 1978). We also argued how embodied signatures such as the ± five-break effect (Domahs et al., 2008) persist throughout childhood and into adulthood and impact numerical choices. In this Chapter, I want to further differentiate how finger use such as counting and gesturing contribute differently to the understanding of magnitude, ordinality, and cardinality. I do so because the GMS proposed by ATOM (Walsh, 2003, 2015) and finger use might constitute two different mechanisms on how we represent numerical knowledge (Sixtus et al., 2023).

Recently, a debate about how we represent mental concepts emerged that proposes different sources on which we build these mental concepts (Borghi et al., 2023). For instance, the conceptualization hypothesis that is part of the embodiment framework suggests that mental concepts are grounded in the sensorimotor system. Whenever we retrieve such concepts their meaning is supported by the activation of the sensorimotor system (Barsalou, 2008; Matheson & Barsalou, 2018; also see Muraki et al., 2023). While this view is widely acknowledged, it can be argued that it lacks specificity. Concretely, from this view "grounding" does not differentiate between innate and learned mechanisms. For example, ATOM's GMS is believed to operate from birth (Walsh, 2003). At the same time, ATOM proposes that sensorimotor interactions with our environment further shape our understanding of within-magnitude dimensions. Therefore, it is unclear what exactly and by how much the GMS and sensorimotor interactions might contribute to the mental concepts involving the within-magnitude dimensions. To quantify their distinct contributions, it is useful to separate the two mechanisms. Indeed, according to M. H. Fischer (2012; for an overview see Borghi et al., 2023; also see Hartmann, 2022) the term “grounded cognition” should be attributed to the physical constraints of our environment and the invariant physical laws of our planet. Our bodies adapted to the environments of our planet and are capable of perception and actions in certain ranges. For instance, the sensitivity of perception can be described by Weber’s law and constitutes a natural constraint. At the same time, we *know* that objects fall downwards and make a pile that accumulates. These associations also reflect universal metaphors such as “more is up” (Lakoff & Johnson, 1980). Grounded cognition can be regarded as the core system of knowledge that has a neuronal basis (Spelke & Kinzler, 2007). Therefore, grounded cognition means the grounding of cognition within the universal constraints of the environment (M. H. Fischer, 2012). Finally, ATOM (Walsh, 2003, 2015) and grounded cognition seem to share the proposition that some magnitude processing operates from birth. This could be a point of connection between the two. Grounded cognition can help extend ATOM by defining universal constraints while ATOM can help grounded cognition by proposing a common processing mechanism for the within-magnitude dimensions.

In addition to grounded cognition, we have knowledge that is acquired through sensorimotor interactions with our world. In M. H. Fischer’s (2012) taxonomy this is termed “embodied cognition”. Embodied cognition is acquired by individual sensorimotor learning histories. For example, sensorimotor experiences of finger use such as finger counting help acquire the numerical concepts described in Chapter 1.3 and Article 1. In terms of Article 1 and how fingers and hands might “embody” cognition, most of us are born with 10 fingers that are arranged between two hands. This is a natural constraint of our bodies and if hands and fingers are used to convey numerical information this specific configuration provides certain limits. Within this natural constraint, there are also individual sensorimotor histories that contribute to conceptual learning (including cultural influences; Shaki et al., 2009). For instance, when children start to learn counting on their fingers they start associating a full hand with the set of five. However, when they start learning the base-10 system, they make frequent errors and systematically deviate by five from the correct result (the ± five-break effect; Domahs et al., 2008). While the 10 fingers between the two hands provide universal constraints to convey numerical information, the individual sensorimotor experiences utilize such a configuration to embody that knowledge. Therefore, embodied cognition refers to the individual sensorimotor contributions to conceptual knowledge while acknowledging the universal constraints of the body (M. H. Fischer, 2012). This account is also in line with ATOM and the notion that actions develop the GMS (Walsh, 2003, 2015), even though embodied cognition further specifies how this happens. Overall, taking the developmental perspective described in Article 1 enables us to theorize about relevant features such as whether the finger-number relations are grounded (natural constraints) or embodied (individual sensorimotor histories), and how exactly they contribute to conceptual knowledge. Finally, ATOM implicitly acknowledges embodied cognition by suggesting that sensorimotor interactions with the environment and actions shape the GMS. Such experiences then contribute to the asymmetrical representation of within-magnitude dimensions. This is due to the learning history with the within-magnitude dimensions not being symmetrical for all these dimensions (Walsh, 2015). Simultaneously, this also can be a point of critical difference between ATOM and embodied cognition. Embodied cognition could contribute to a new form of representation outside and independent of the GMS such as that of spatial processing of ordinality (Sixtus et al., 2023).

Overall, grounded and embodied cognition are organized hierarchically and displayed in their stability and strength to represent conceptual knowledge (M. H. Fischer, 2012). Hereby, grounded cognition would be most stable; however, embodied cognition is stronger and "overrules" grounded cognition under situated task demands that require flexibility. Again, this could be a point of connection between ATOM and grounded-embodied cognition. Indeed, ATOM proposes that at some point, the processing of with-magnitudes transitions from being processed equally to perhaps hierarchically (Walsh, 2015). Capturing such transition would benefit ground-embodied cognition as well as ATOM as both propose strong developmental influences.

3.2 Continuous and Discrete Magnitudes

Recently, it was proposed that ordinality, cardinality, and magnitude are three distinct semantic concepts with each being represented differently by our sensorimotor system (Sixtus et al., 2023). The semantic concept of magnitude is based on an analog and approximate representation of continuous amounts (Leibovich et al., 2017; Rinaldi & Girelli, 2017; Sixtus et al., 2023). For example, when a set of items increases, the cumulative area of the items, the overall area, and the density of the area also increase (Leibovich et al., 2017). Therefore, the understanding of the semantic concept of magnitude is in line with the assumption of the GMS of ATOM in which "more" in one within-magnitude dimension is also "more" in another (Walsh, 2003, 2015). Using the grounded-embodied taxonomy defined earlier (Chapter 3.1) the semantic concept of magnitude is *grounded* in the GMS.

In addition to the GMS, semantic numerical magnitudes can also be *embodied* through sensorimotor experience of finger use. For instance, representing larger quantities through fingers such as counting will require moving more fingers to form a hand gesture that also automatically will occupy a larger visual space that produces "more action" than a gesture representing a smaller quantity. Therefore, magnitudes are also embodied in the

GMS in visual and motor magnitudes through sensorimotor experiences of finger use such as counting (Sixtus et al., 2023).

Moreover, finger counting can help acquire discrete numerical knowledge (for an overview see Barrocas et al., 2020). For instance, finger counting can shape the association between fingers and space and contribute to the understanding of ordinality. Indeed, in Western societies, it is typical to start counting on the left hand through the numbers from 1 to 5 and then continue counting from 6 to 10 on the right hand. With such finger counting behavior, smaller numbers are more likely to be associated with the left space and larger numbers with the right space (M. H. Fischer, 2008; M. H. Fischer & Brugger, 2011; Lindemann et al., 2011). Such finger counting behavior can contribute to the tendency to order magnitudes such as numbers on a mental number line on which smaller numbers are represented to the left or larger numbers (Dehaene et al., 1993; Restle, 1970). Hereby, such spatial ordering is based on the concept of ordinality that is discrete and independent of approximate magnitudes represented by the GMS (Sixtus et al., 2023). According to Sixtus et al. (2023), ordinality is shaped directly through finger counting and is represented independently from the GMS as a spatial ordering account. However, as the authors draw double arrows indicating dependencies between fingers and the GMS, fingers and the spatial ordering account, and spatial ordering account and the GMS, it seems that they all are deeply intertwined.

Finally, finger counting also contributes to the understanding of cardinality. When fingers are used to count, the last finger also represents the last item in a set and results in the final hand gesture, therefore, representing the discrete numbers of items in a set (Di Luca & Pesenti, 2008; Sixtus et al., 2018). The main difference between cardinality and magnitude is that cardinality (as is ordinality) is discrete and precise while magnitude is approximate (Sixtus et al., 2023). For this Thesis, cardinality is not the focus but is still to be considered as all numerical tasks of the empirical work utilized Arabic numerals (digits and words) in the ranges from 1 to 9, meaning, that it could have had some unpredictable influences on the outcomes.

To conclude the Chapter, grounded cognition assumes a fundamental role of the universal constraints of the environment on cognition. The GMS is a common processing mechanism for within-magnitude dimensions and is believed to operate from birth. Both seem to operate on a similar level that I interpret as a point of connection. Embodied cognition assumes a fundamental role of the universal constraints of the body on cognition. Embodied cognition can connect to the GMS by shaping the GMS through individual sensorimotor histories. It also could critically differ from the GMS by contributing to a new and independent source of knowledge as a mechanism of spatial processing of ordinality. Therefore, both sources of grounded and embodied cognition contribute differently to the semantic concepts of magnitude, ordinality, and cardinality. The GMS as well as finger use capture the *semantic concept of magnitude by grounded and embodied mechanisms*. Additionally, *finger counting and gesturing contribute to the semantic concept of cardinality by embodied mechanisms*. Additionally, *finger counting contributes to the semantic concept of ordinality by embodied mechanisms* that shape spatial ordering that is independent of the GMS. Overall, connecting and comparing different mechanisms of conceptual knowledge can be beneficial for theoretical development to be tested empirically. This constitutes the primary aim of this thesis: testing the direct coupling of the within-magnitude dimensions of number magnitudes and motor magnitudes in and outside of spatial conditions. With numbers, we manipulated semantic numerical magnitudes. With spatial conditions, we manipulated either continuous space or ordinal space.

Part II: Empirical Work

Chapter 4: Experimental State of the Art

4.1 Dichotomous Associations in Mental Chronometry

In this Chapter, I will provide insights into two effects that tested the within-magnitude dimensions of motor magnitude and space relevant to our own work: the Spatial Numerical Associations of Response Codes (SNARC; Dehaene et al., 1993) effect and the Force-Numerical Association of Response Codes (FoNARC; Krause et al., 2014; Vierck & Kiesel, 2010) effect. I describe the two effects in detail as they are prototypical examples of a rich and diverse field of dichotomous associations (for a meta-analysis of such effects see Macnamara et al., 2018). Both effects have a history of being measured under the reaction times paradigm (not exclusively) that I will contrast to the continuous recordings used in our empirical work. For this, I will describe how responses are measured and what it means for research in and outside of the embodied cognition framework.

First, the SNARC effect describes that people respond faster to smaller numbers on the left side and faster to larger numbers on the right side (Dehaene et al., 1993). The SNARC is a well-established phenomenon that describes the tendency for faster responses to smaller numbers in the left space and larger numbers in the right space. Therefore, people associate smaller numbers with the left space and larger numbers with the right space. Second, the FoNARC effect (Krause et al., 2014; Vierck & Kiesel, 2010) describes how participants tend to respond faster to smaller numbers with soft force and respond faster to larger numbers with strong force. Therefore, FoNARC describes the tendency to associate smaller numbers with soft response types and larger numbers with strong response types. Both of the introduced effects utilize the parity classification task in which participants are asked to classify numbers as odd or even. Usually, the parity classification task includes the number range from 1 to 9 providing the categorical independent variable (even vs. odd). The parity classification task assumes that the number magnitude becomes activated automatically (small vs. large) even though the explicit instructions are based on parity (Dehaene et al., 1993). In the original SNARC test described above, the responses to the task are given in the form of button presses that are aligned spatially (left vs. right). In the grounded-embodied taxonomy of Chapter 3, ordering numbers based on their parity and space points to spatial processing based on ordinality. Therefore, I classify the SNARC effect as a product of explicit spatial processing that orders numbers on a horizontal mental number line with smaller numbers being to the left of larger numbers (Restle, 1970). The responses are the recorded dependent variable and provide one data point being the reaction time that is measured as the difference between stimulus and response onset (response onset minus stimulus onset). In the FoNARC tests introduced above, the responses are recorded by a centrally placed button. In addition to the one reaction times data point, the button also records the applied force, therefore having two dependent variables: reaction times and force peaks. Usually, the applied force produces one additional data point being the force peak that was produced during the trial. Crucially, the associations reported by the FoNARC experiments were only found in the reaction times and not in force peaks. Therefore, the total force of numbers does not differ between small and large numbers which means that it is not evidence for a direct coupling between number magnitudes and motor magnitudes. It means that the effect is a pure association of numerical magnitudes and dichotomous response types found in reaction times (smaller number/soft response type vs. larger number/strong response type).

The reaction times paradigm is a fundamental part of mental chronometry that “is the measurement of cognitive speed” (Jensen, 2004, p. 26). At its core are the binary decisions between stimulus and response that are reported as dichotomous associations. This is true for the SNARC effect, the FoNARC effect as well as all the dichotomous size congruency effects described in Chapter 1. While such dichotomous associations can be explained by ATOM (Walsh, 2003, 2015), it does not necessarily mean that these effects are embodied. This is due to how effects from the reaction time paradigm can be interpreted and at what stage between stimulus and response they actually occur.

There are three stages of the possible emergence of an effect during the reaction time paradigm that I consider here: an early stage during stimulus processing, a later stage of response selection, and a late stage of response execution. Taking the SNARC effect described above as an example, an early stage would mean that the mental representation of a number also activates its spatial representation with smaller numbers being to the left of larger numbers. A later stage would then map this mental representation onto the available responses of left and right while the late stage would produce an effect after response selection (for instance by measuring force; see R. Fischer & Miller, 2008). Considering both, the SNARC as well as the FoNARC effect, it is likely that these effects have a later origin during the response selection stage rather than an early origin during the stimulus stage. For instance, a study tested the origins of the SNARC by adding one manipulation to the original design (Keus & Schwarz, 2005) under which the SNARC effect was first reported (Dehaene et al., 1993). Instead of centrally presented number digits, Keus and Schwarz (2005) manipulated the spatial placement of the digits to the left and right of the fixation cross. The placement of the digits to the right or left was either congruent (small number and left space) or incongruent (small number and right space) and the responses were on the left and right side as in the original design. The main finding was that there was no interaction between the number magnitude and the presentation side while finding the traditional SNARC (also see Gevers, Ratinckx, et al., 2006; Keus et al., 2005). Due to their results, the authors concluded that the origins of the SNARC effect are most likely during the response selection stage rather than the stimulus stage. To be more specific, the SNARC effect likely originates from the response selection rather than the response execution stage indicated by response-locked event-related potentials (Keus et al., 2005). Adding to that, the FoNARC effect is an association between number magnitude and dichotomous response types (small number – soft force vs. large number – strong force). This association occurred at the response selection stage while there was no effect of number magnitude on motor magnitudes during the response execution stage. In sum, SNARC and FoNARC are likely to be effects that emerge during the response selection stage. Due to such dichotomous associations, both the SNARC as well as the FoNARC effect explain how stimulus and response are classified by response selection but not quantified by response execution. Therefore, other non-embodied theories such as the polarity-correspondence account (see Chapter 1; Proctor & Cho, 2006; Proctor & Xiong, 2015) can also interpret pure dichotomous stimulus-response associations because they neglect action execution.

Finally, it is proposed that at least some of such dichotomous associations should not be interpreted as evidence for ATOM. This is because their relation is based on metathetic and qualitative (Casasanto & Pitt, 2019) rather than prothetic (Stevens, 1957) and continuous variations as described in Chapter 1. Critically and based on the above arguments, it is my personal interpretation that the FoNARC effect (Krause et al., 2014; Vierck & Kiesel, 2010) should not be interpreted as evidence for ATOM (Walsh, 2003, 2015) because it is a pure association of metathetic labels that were not quantified in the prothetic dimension of force as quantifiable peak forces. It differs from the interpretation that "soft response types" are still "less of an action" than "strong response types" which are "more of an action" (Sixtus et al., 2023). While I think that response types are labels that are purely metathetic and qualitative, Sixtus et al. (2023) directly compared response types to peak forces that were found in another study (Krause et al. 2019) that actually quantified the responses during execution. Therefore, I classify the FoNARC effect as a product of dichotomous associations between metathetic labels for numbers and response-types. This is the reason why it is critical to quantify effects beyond action initiation in order to provide strong evidence for embodied effects.

In conclusion, non-embodied theories based on stimulus-response compatibilities described above can explain effects based on binary decisions. However, their explanation does not go beyond the response selection stage. Whenever an effect is found during the response execution stage, these accounts lose their explanatory power as they cannot account for the quantification of a response while embodied cognition accounts can. Therefore, showing a direct coupling between semantic numerical magnitudes and motor magnitudes would be strong evidence pointing to an embodied signature of numbers.

4.2 Action Execution and Continuous Force Recordings

In order to interpret effects within the embodied cognition framework, we decided to measure response execution with force recordings in our own work. There were two ways how we utilized these force recordings: as active responses and as passive continuous force recordings. Overall, the force recordings have three major advantages over reaction time measures described earlier. First, active responses as well as passive recordings are capable of measuring motor control and execution. It provides additional data informing about action execution after the response is already selected (Balota & Abrams, 1995). Second, passive force recordings can also be measured continuously. Such continuous force recordings provide a force profile for the entire duration of a trial that depicts the sum of cognitive processes on a temporal continuum. The method is highly sensitive and provides a 1000 Hertz (Hz) resolution (cf. Nazir et al., 2017). Third, passive continuous force recordings do not require any active responses. During a cognitive task, participants are asked to hold the force sensor in a precision grip while applying slight and steady pressure to it. This procedure ensures that the sensor does not slip the grip and that participants do not intentionally apply more or less force. The product is the force profiles that depict spontaneous grip force fluctuations during the cognitive processing of which participants should be unaware. Therefore, force recordings can show embodied signatures of cognitive processes by measuring action execution. In addition, continuous force recordings can depict the progress of a cognitive process on a temporal continuum that proves a 1000Hz resolution instead of just one data point. In conclusion, force recordings allow us to test predictions made by ATOM (Walsh, 2003, 2015) and classify them as embodied effects if they can be quantified during action execution.

Such continuous force recordings are quite novel but are already successfully applied in the embodied cognition framework. For instance, previous studies from linguistics have utilized the grip force measures to understand the processing of action-related language. These studies found that the processing of action verbs and action contexts can be depicted in increasing grip force compared to non-action content (Aravena et al., 2012, 2014; Frak et al., 2010; Nazir et al., 2017; Pérez-Gay Juárez et al., 2019; for action simulation also see Blampain et al., 2018). These studies clearly demonstrate the involvement of the motor system and motor control during the processing of action language accumulating validity for this method. A direct involvement of the motor system and motor control and execution modulated by action language is therefore evidence that grip force is an embodied signature of language processing. Such a measure of motor control and execution is a direct extension of the reaction time measurements that only measure response selection. However, measuring response execution is crucial to quantify embodied cognition effects. While non-embodied theories can explain effects during reaction times (Gevers et al., 2010; Proctor & Cho, 2006; Proctor & Xiong, 2015), they cannot predict or explain effects measured during action execution.

Chapter 5: Experimental Strategy

The primary aim of the experiments was to test the direct coupling of the within-magnitude dimensions of semantic numerical magnitudes and motor magnitudes with and without spatial interactions. As this specific research question and the novel continuous force recordings (see Chapter 4) are not well represented in the literature, the estimation of possible effect sizes was not considered. Therefore and to maximize internal validity, we decided to conduct all the studies within highly controlled laboratory environments. Table 1 in the Chapter "Project Overview and Aims" summarizes all our research questions. To note, within all studies reported here we utilized number symbols and words to access semantic numerical meaning. Therefore, whenever I refer to numerical magnitudes, number magnitudes, or simply numbers, the magnitude representation of the magnitude is exact.

We decided to start broad and test a direct coupling of number magnitudes and motor magnitudes during continuous spatial conditions in Study 1. To activate the magnitude of a number we decided to use the random number generation task (e.g., Shaki & Fischer, 2014). To activate spatial information we asked participants to continuously apply isometric force in the directions of either left, right, down, or up. The study aimed to answer two research questions. First, does random number generation affect motor magnitudes? Second, does directional force production affect random number generation? Therefore, we define continuous spatial conditions as conditions in which participants were instructed to continuously press into only one direction at a time. Such spatial conditions aimed to manipulate continuous space. In the final results of this study, we found evidence (Bayesian statistics) that there was no support for both of the research questions.

At this point, there were two possible ways to continue. Option 1 was to focus on the direct coupling between number and motor magnitudes. Option 2 was to focus on the coupling between number and motor magnitudes in spatial conditions. I decided to stick with option 1 and designed Study 2. As the results of Study 1 indicated no effects across the research questions, I decided to optimize and increase the sensitivity of the experimental design to find a possible coupling between number and motor magnitudes. For this, I decided to change both, the task as well as the measurement of Study 2 compared to Study 1. The final results of Study 2 were positive and we found a direct coupling between number and motor magnitudes. Smaller numbers induced smaller motor magnitudes while larger numbers induced larger motor magnitudes. These findings were in line with ATOM that also would predict such a positive correlation between magnitudes (Walsh, 2003, 2015).

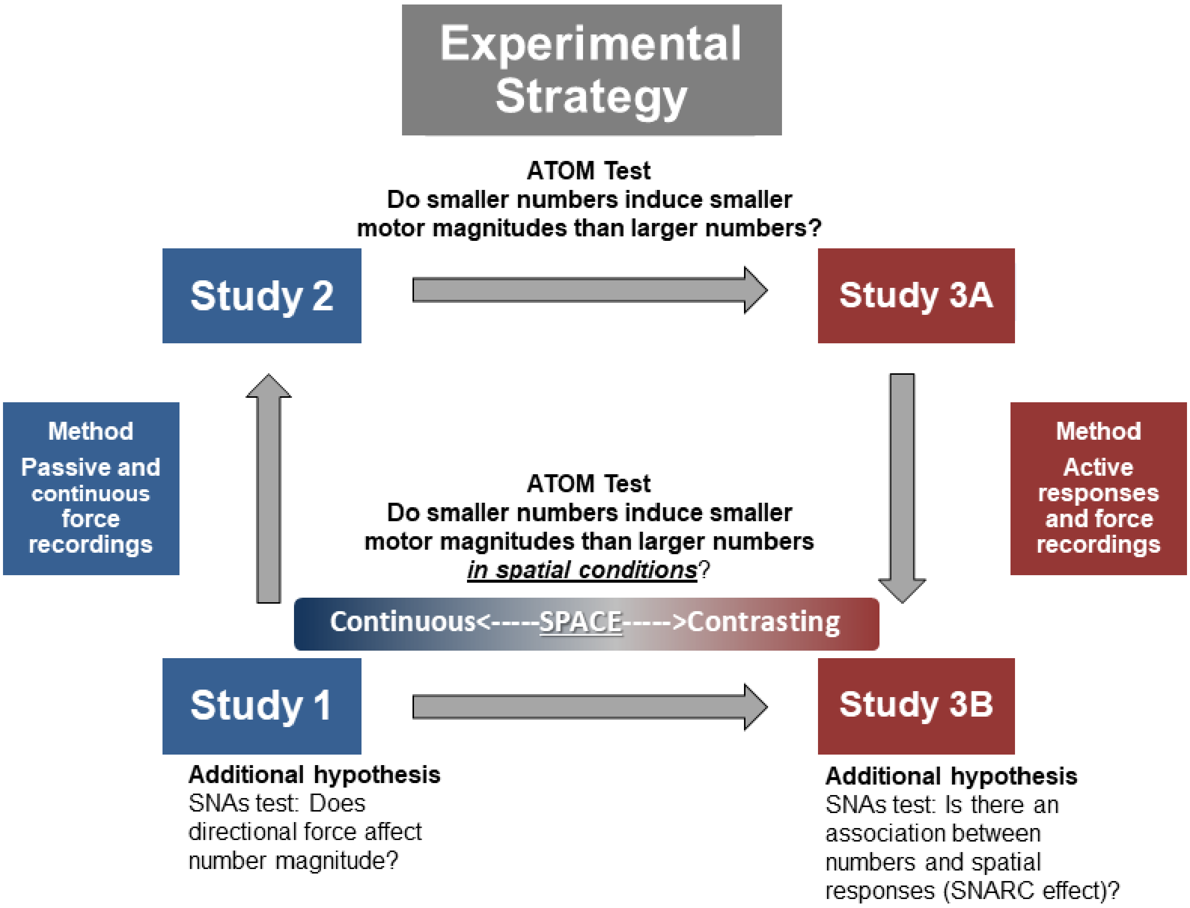
The results of Studies 2 and 1 provided essential results and opened up several possibilities on how to pursue the experimental strategy. First, Study 2 described a direct coupling between number and motor magnitudes. Second, Study 1 described no such direct coupling between number and motor magnitudes during continuous spatial conditions. Finally, we decided to combine and extend both and test the direct coupling between number and motor magnitudes with and without spatial conditions.

For this, we constructed two additional Studies 3A and 3B. Study 3A tested the direct coupling between number and motor magnitudes outside of spatial conditions and during active responses. Study 3B tested the coupling between number and motor magnitudes in spatial conditions also during active responses. As both studies were designed together with the intention to complement each other, the motivation to use active responses instead of passive readings was motivated by Study 3B described beneath.

Study 3B was motivated by Study 1 in which we found that continuous spatial conditions did not induce spatial processing. Therefore, we decided to opt for spatial conditions that are known to elicit spatial information. The literature revealed that in order to obtain a strong spatial effect (e.g., the SNARC effect; Dehaene et al., 1993), both number magnitude as well as spatial contrasts in the response space need to be activated (Pinto, Pellegrino, Lasaponara, et al., 2019, 2021; Pinto, Pellegrino, Marson, et al., 2019, 2021). We decided to rely on the state of the art and utilized two well-researched methods on how to obtain spatial effects. For this, we opted for the magnitude classification task because it produces high effect sizes for the described SNARC effect (Wood et al., 2008). In our magnitude classification task participants were asked to classify a number as either “smaller” or “larger than the reference point five”. Second, we opted to measure motor magnitudes, but this time we asked participants to actively press the sensors instead of passive readings (as in Studies 1 and 2). Hereby, active responses ensured that participants explicitly knew that the response was classified as either “left” or “right”. Together, the magnitude classification task and the active presses in spatial conditions ensured explicit spatial processing. This is due to the task instructions to classify a number as “smaller” or as “larger than five” by responding in either the “left” or the “right space”. Therefore, explicit spatial processing is defined by ordinality and as the activation of spatial information that is needed to order “smaller” and “larger numbers” either ”to the left” or “right” during responses. As described in Chapter 3, such spatial processing might operate differently from the GMS by relying on the semantic concept of ordinality (Sixtus et al., 2023). Therefore, it enables a comparison to Study 1 which has utilized continuous spatial conditions that we defined as a continuous manipulation of space. The results of Studies 3A and 3B are discussed in Chapter 8. Figure 1 provides the full overview of the four studies described in this Thesis.

Figure 1

The experimental strategy of this Thesis.



Note. The figure includes the abbreviations ATOM, SNAs, and SNARC. ATOM stands for A Theory of Magnitude (Walsh, 2003, 2015), SNAs for Spatial Numerical Associations, and SNARC for Spatial Associations of Response Codes (Dehaene et al., 1993).

Chapter 6: Study 1

6.1 How to not induce SNAs: The insufficiency of directional force

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Abstract:

People respond faster to smaller numbers in their left space and to larger numbers in their right space. Here we argue that movements in space contribute to the formation of spatial-numerical associations (SNAs). We studied the impact of continuous isometric forces along the horizontal or vertical cardinal axes on SNAs while participants performed random number production and arithmetic verification tasks. Our results suggest that such isometric directional force do not suffice to induce SNAs.

Chapter 7: Study 2

7.1 Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces

Submitted as:

Michirev, A., Lindemann, O., Kühne, K., Fischer, M.H., & Raab, M. (submitted). Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces.

Abstract:

This study investigated the relationship between semantic numerical magnitudes and motor magnitudes. For this, we recorded continuous grip force fluctuations from 43 healthy adults during a symbolic magnitude comparison task. We found that numbers induced spontaneous grip force fluctuations during number processing. Smaller numbers induced lower grip forces, whereas larger numbers induced larger forces. This result constitutes strong behavioral support for a generalized magnitude processing by continuously quantifying the response that challenges binary accounts of cross-domain interactions.

Appendix 3

Chapter 8: Studies 3A and 3B – Active and Forceful Responses

8.1 Overview, Motivation, and Theoretical Predictions

The overall aim of this Chapter is to describe two studies that were part of the research project introduced in Chapter 5. For this, I integrated them into the experimental strategy (Figure 1 in Chapter 5) rather than writing them up as one independent manuscript. Therefore, I will present the information that I find necessary while omitting others. More detailed (yet preliminary) analyses for these two studies are uploaded to the open science framework (see **Project Overview and Aims** on page xv).

Studies 3A and 3B were constructed to systematically test how number magnitudes affect motor magnitudes with and without spatial conditions during active responses. These studies were based on the results of Studies 1 and 2. In Study 2 we found number-force magnitude associations that describe a direct coupling between number magnitudes and motor magnitudes as predicted by ATOM (Walsh, 2003, 2015). In Study 1 we found no such associations; we also did not find any effects of continuous force production applied in a spatial direction during number generation. One of the explanations why we did not find any effects of spatial conditions was that we utilized continuous directional force (e.g., pressing to the left while generating numbers) and therefore lacked spatial contrasts (e.g., deciding to press to the left or right as response to a number). However, such spatial contrasts are critical to induce spatial processing that is necessary to elicit spatial numerical associations (Pinto, Pellegrino, Lasaponara, et al., 2019, 2021; Pinto, Pellegrino, Marson, et al., 2019, 2021). These empirical findings are in line with the proposal that spatial ordering, such as the mental number line (Restle, 1970), utilizes the semantic concept of ordinality that is independent of ATOM (Sixtus et al., 2023). Therefore, spatial numerical associations found with spatial contrasts might not represent true evidence in favor of

ATOM, but rather that of spatial ordering (Casasanto & Pitt, 2019; Sixtus et al., 2023). The current two studies aimed to test whether ATOM and spatial ordering are indeed independent by measuring motor magnitudes in response to number magnitudes with and without spatial conditions. I theorize that if all the within-magnitude dimensions are processed by a common mechanism, then number magnitudes should always produce larger motor magnitudes (as predicted by ATOM and found in Study 2). However, if there is an independent processing mechanism for spatial order, then number magnitudes could interact with that spatial information and therefore produce motor magnitudes that are a product of such an interaction (based on Casasanto & Pitt, 2019; and Sixtus et al., 2023).

For Study 3A we did not introduce a spatial condition. Therefore, and in line with ATOM, we predicted that responses to smaller numbers would produce smaller motor magnitudes than responses to larger numbers (Walsh, 2003, 2015). For Study 3B, we introduced spatial conditions as lateralized responses in the left and the right space. We predicted that we would find a typical SNARC effect (Dehaene et al., 1993). Participants would make faster responses to smaller numbers in the left space and faster responses to larger numbers in the right space. Additionally, following the predictions of ATOM, we predicted that responses to smaller numbers would produce smaller motor magnitudes than responses to larger numbers independently from the spatial side of the responses. As proposed above, if indeed ATOM and spatial ordering are independent it would be possible that the interaction of number magnitude and spatial responses would affect motor magnitudes differently depending on the response side.

There are two theoretically valid explanations for such interactions that are independent of ATOM (Walsh, 2003, 2015). One of those highlights the compatibility between numbers and space. For instance, there is a tendency to organize smaller numbers to the left of larger numbers which can be referred to as the mental number line (Dehaene et al., 1993; Restle, 1970). In this scenario, smaller numbers are compatible with the left space while larger numbers are compatible with the right space. Whenever the number magnitude and the lateral side match (small/left and larger/right) responding is easier and produces smaller motor magnitudes. Whenever the number magnitude and the lateral side mismatch, responding is more difficult and would result in larger motor magnitudes.

The other theoretical prediction is based on the confidence model described by Balota and Abrams (1995). The confidence model originated from linguistics and describes how high-frequency words are associated with more evidence because people are more familiar with them in contrast to low frequency words. The authors found the frequency of words also directly affects the production of motor magnitudes. When participants responded to high-frequency words they produced larger motor magnitudes than when they responded to low-frequency words. For Study 3B, this would mean that participants would attribute evidence based on the compatible matches between numbers in space. Whenever smaller numbers and the left space are matched they also produce high confidence which results in larger motor magnitudes in the response. The same would be true whenever larger numbers and the right space are matched. Overall, the confidence model is in direct contrast to the above-introduced prediction based on difficulty.

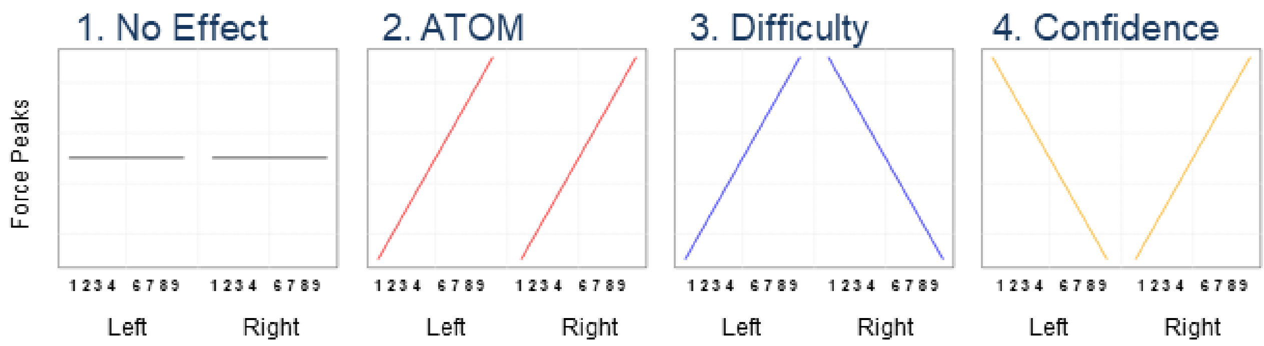
In sum, there are four possible directions of the effect (see Figure 2 for visual representation).

1. There is no effect of number magnitude on motor magnitudes.
2. ATOM: Responses for smaller numbers will produce smaller motor magnitudes than for larger numbers independent from the response space.

3. Difficulty: In the left space, responses for smaller numbers will produce smaller motor magnitudes than for larger numbers. In the right space, responses for smaller numbers will produce larger motor magnitudes than for larger numbers.
4. Confidence: In the left space, responses for smaller numbers will produce larger motor magnitudes than for larger numbers. In the right space, responses for smaller numbers will produce smaller motor magnitudes than for larger numbers.

Figure 2

Visual representation of the four models and predicted effect directions.



Overall, Studies 3A and 3B were constructed to be directly comparable to each other while also extending the findings of Studies 1 and 2 (see Figure 1 in Chapter 5). At this point, both studies are yet unpublished and the described results are preliminary. Data acquisition of Study 3A is concluded (*n* = 40) while it is still collected for Study 3B (*n* = 27).

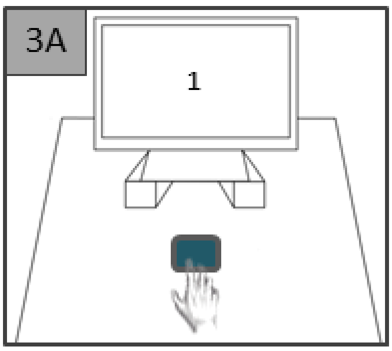
8.2 Study 3A

In Study 3A, we aimed to establish a within-magnitude effect between number and motor magnitudes during active responses. Therefore, and as described above we aimed to test the predictions of ATOM and if responding to larger numbers would also result in larger motor magnitudes than responding to smaller numbers. Thus, Study 3A served as a conceptual replication of Study 2 within a different experimental set-up.

We utilized the magnitude classification task with number stimuli in the range of 1 to 9 and the reference 5. Each stimulus was presented for 2 seconds. The stimuli were presented across two blocks in a counterbalanced order. We utilized the Go/NoGo paradigm (e.g., Georgiou & Essau, 2011) in which participants needed to respond when they saw a small number (<5) in one block and in the other block when they saw a large number (>5). Responses we recorded by the same sensors as in Studies 1 and 2 but this time were fixated centrally on the table (Figure 3). Participants were asked to apply small pressure (in the range between 1500 and 3000 Millinewtons) to the sensor at all times with their index and their middle fingers. During the Go trials, participants were instructed to press the sensor as if it were a button while no responses were required during the NoGo trials. The sensor was again placed centrally and aligned to the presentation space of the stimuli on the horizontal axes (similar to Study 2).

Figure 3

Schematic overview of the experimental set-up of Study 3A.



Note. The blue square represents the sensor fixated on the table. In Study 3A the sensor was placed centrally on the table and aligned with the stimuli on the horizontal axis. At all times participants pressed the sensor with the index and middle fingers. Active responses required to press the sensor as if it were a button.

Our recorded force data was continuous in nature and similar to the data of Studies 1 and 2. However, the major difference was that active responses produced force peaks that we analyzed. Such data structure has the advantage that both, reaction times as well as force peaks can be recorded at the same time. Reaction times were defined as the time between stimulus and movement onset. Movement onset was identified as the time point x if followed by a velocity increase of 800 Millinewtons (mN) or more within the next 200ms. Force peaks were defined as the higest force between movement onset and movement offset. Movement offset was identified identically to the movement onset, but mirrored. For this experiment, the reaction times are a side measure and a by-product of the method as it required active responses. It is still relevant because it can be compared to the onset of magnitude processing in Study 2. These reaction times will become statistically relevant in Study 3B and the overall discussion. For Study 3A, the force peaks are of the most interest as they represent the motor magnitudes produced during response execution.

We analyzed the force peaks with a linear mixed effect model (MixedModels.jl package; Bates et al., 2020). The analyzed data set concluded 37 participants with 336 experimental trials per participant resulting in a total of 12432 experimental trials. Given we utilized the Go/NoGo paradigm, only half of those trials were the Go-trials that required active responses resulting in a total of 6216 trials. Only the Go-trials were analyzed. Number was the independent variable, continuous, and coded as a fixed factor with random slopes of numbers for participants. The reaction times did not significantly differ between small and large numbers (p = .82). The reaction time of the grand mean in the study was 487ms. Peak force did not significantly differ between small and large numbers (p = .57).

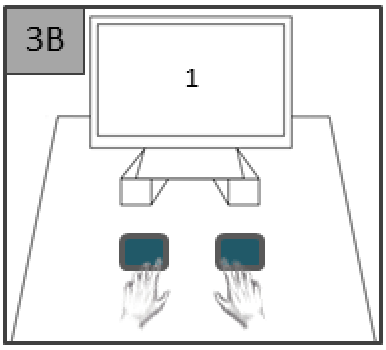
These results contradict our findings of Study 2 and the predictions of ATOM. Number magnitude did not affect force magnitudes. At the same time, these results are in line with the previous studies that also did not find any force peak differences between smaller and larger numbers during active responses and action execution (R. Fischer & Miller, 2008; Krause et al., 2014; Vierck & Kiesel, 2010). As these studies utilized parity classifications, we extend these null findings to magnitude classifications.

8.3 Study 3B

In Study 3B we aimed to measure a within-magnitude effect between number magnitudes and motor magnitudes during active responses in spatial conditions. For this, Study 3B utilized the same task, the same measurements, and the same response types as Study 3A. In this regard, both studies are symmetrical and directly comparable. However, in contrast to Study 3A, Study 3B introduced lateral response space. Therefore, it also served as a conceptual replication of the original SNARC study (Dehaene et al., 1993) that measured motor magnitudes in addition to reaction times. Study 3B differed in two regards from the experimental paradigm of the original SNARC study. As for the first change, we utilized the magnitude classification task instead of the parity classification task because it activates explicit magnitude processing of the number magnitude and also produces higher effect sizes of the SNARC effect (Wood et al., 2008). As in Study 3A, we utilized stimuli in the range from 1 to 9 and reference 5. Again, each stimulus was presented for 2 seconds. The stimuli were presented across two blocks in a counterbalanced order. In one block, participants needed to respond when they saw a small number (<5) with their left hand and to larger numbers (>5) with their right hand. The spatial-response mapping was reversed in the other block. As for the second change, we utilized two force sensors instead of the two buttons allocated on the left and the right response space (see Figure 4). Again, participants were asked to apply small pressure (in the ranges between 1500 and 3000mN) to both sensors at all times with their index and their middle fingers. When a response was required, participants were instructed to press the sensor as if it were a button. The data structure was the same as in Study 3A additionally adding the new factor “response” given in the left or right space. Overall, the magnitude classification task and active spatial responses introduced explicit spatial processing to the study that allowed testing interactions between number magnitude and the response space. It is the major difference to the method of Study 1 that has utilized continuously applied directional force without spatial contrasts and a verbal production task without a reference.

Figure 4

Schematic overview of the experimental set-up of Study 3B.



Note. The blue squares represent the sensors fixated on the table. In Study 3B two sensors were placed laterally on the left and the right side. At all times participants pressed the sensor with the index and middle fingers. Active responses required to press the sensor as if it were a button.

To ensure that we indeed replicated the described SNARC effect we analyzed the reaction times with the classical SNARC analysis (Fias, 1996). For this, we extracted the individual reaction times for each number from the left and the right side. Then we computed the difference in reaction times by subtracting the right-side reaction times from the left ones and submitted them to a linear regression. Our analysis revealed a significant SNARC effect, $p < .001$. The reaction time grand mean average of this experiment was 455ms. In addition, we analyzed the force peaks with a linear mixed effect model (MixedModels.jl package; Bates et al., 2020). Number was coded as continuous and as a fixed factor. Response was a categorical fixed factor. The model further included an interaction between number and response as a fixed factor and number and response were also added as random slopes for participants. The analyzed data set concluded 23 participants with 336 experimental trials per participant resulting in a total of 7728 experimental trials. The force peaks revealed a significant fixed effect of number $p < .001$, a significant fixed effect of response $p < .001$, and a significant interaction effect between number and response, $p < .001$.

Overall, our results replicated the findings of the original SNARC effect and showed faster responses for smaller numbers on the left side and faster responses for larger numbers on the right side (Figure 5). Additionally, our force peaks data showed that larger numbers as well as the right response are associated with larger force peaks. Therefore, participants applied larger forces while being presented with larger numbers and generally applied larger forces on the right side. Most intriguing is the interaction between number magnitude and responses. On the left side, smaller numbers produced smaller force peaks and larger numbers produced larger force peaks. On the right side, small numbers produced large force peaks and large numbers produced small force peaks (Figure 6).

Figure 5.

The SNARC effect depicted in reaction times.

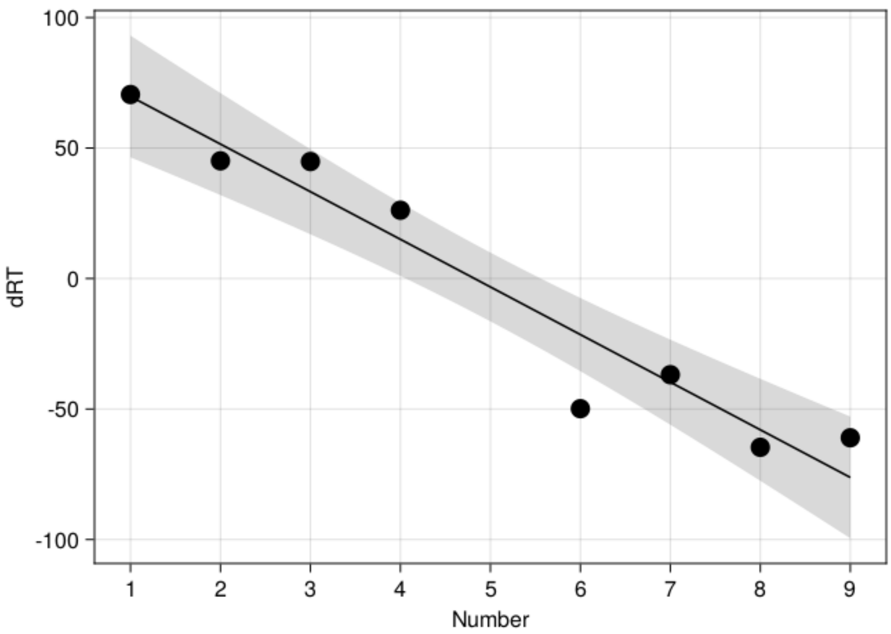
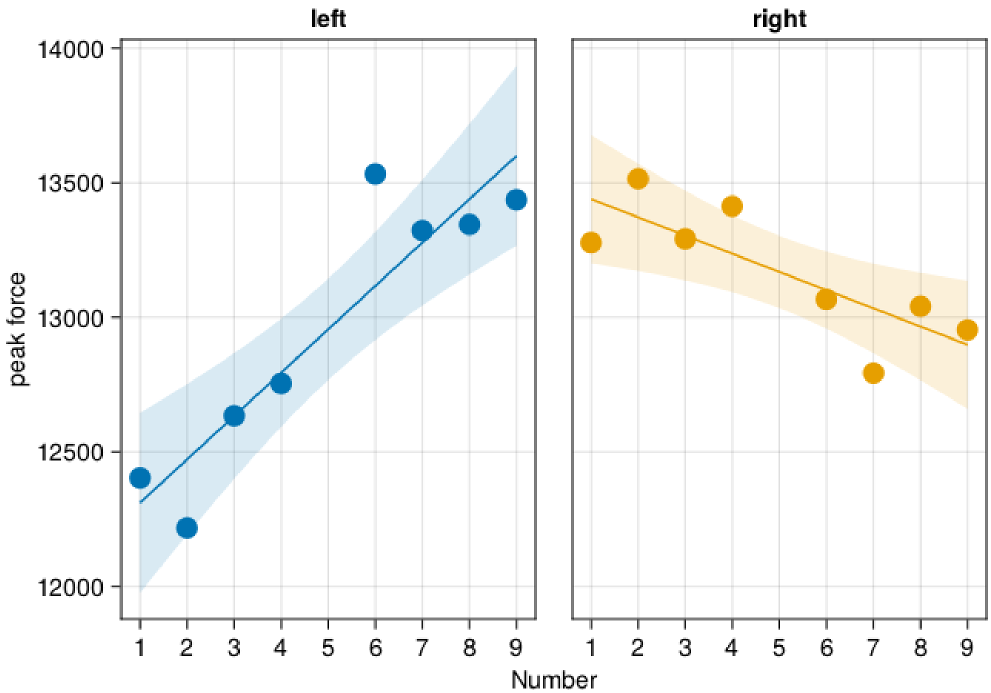


Figure 6.

The manifestation of the SNARC effect in motor magnitudes.



8.4 General Discussion of Studies 3A and 3B

Studies 3A and 3B were designed to investigate a direct coupling between number magnitudes and motor magnitudes with and without spatial contrasts during active responses. The general prediction for Study 3A was based on ATOM (Walsh, 2003, 2015) and that smaller numbers would lead to smaller motor magnitudes while larger numbers would lead to larger motor magnitudes. However, this is not what we found. In Study 3A there was no evidence of a direct coupling between number and motor magnitudes, thus contradicting the predictions of ATOM. This result is in line with previous studies that also did not establish an effect of number magnitudes on motor magnitudes during active and forceful responses (R. Fischer & Miller, 2008; Krause et al., 2014; Vierck & Kiesel, 2010). However, these results contradict the results of Study 2 which found an effect of number magnitudes on motor magnitudes during passive grip force recordings.

There are two explanations for the different results between this study and Study 2. First, it is possible that active responses utilized in this study produced high variations in motor execution incapable of capturing the effects of magnitude processing. If this was the case, then the magnitude processing described in Study 2 produced a rather small effect that needs highly sensitive measurements to be detected (e.g., continuous grip force). Active responses then overshadowed the small effect. Second, the difference in the numerical task and the temporal onsets of magnitude processing could have produced a different "quality" of magnitude activation specific to this task. For instance, the magnitude classification task of Study 3A required classifying numbers as "smaller" or "larger than five". These classifications were produced rather quickly at 487ms and were likely to represent a representation of magnitude meaning specific to classifications. In contrast to this, in Study 2 participants did not need to classify numbers according to "smaller" or “larger than five”. Instead, they passively watched numbers in sequential order while holding them in the working memory. The participants also did not need to make any decisions or actions during these experimental trials. Such a task structure ensured that numbers remained in working memory for the entire trial while anticipating the next trial. Indeed, we observed the onset of magnitude processing at 767ms and until 1158ms which was then followed by another time window between 1465 and 2000ms. During these time windows, larger numbers induced significantly larger motor magnitudes than smaller numbers. However, as both the task structure and the response types differed between the current Study 3A and Study 2, we cannot further specify due to which change exactly we found these conflicting results.

Intriguingly, in Study 3B we also utilized the magnitude classification task and also reported fast responses at 455ms as the grand mean. However, this time there was an interaction between number magnitudes (small vs. large) and spatial responses (left vs. right) displayed in motor magnitudes. In the left space, responses to smaller numbers produced smaller motor magnitudes than to larger numbers. In the right space, responses to smaller numbers produced larger motor magnitudes than to larger numbers (Figure 6). This force data does not depict a profile predicted by ATOM (Walsh, 2003; 2015) and rather fits the predictions of “difficulty” as model three formulated above (Chapter 8.1). Participants must have associated smaller numbers as compatible with the left space that produced faster (as indicated by the SNARC analysis) and also softer responses compared to larger numbers (and vice versa for larger numbers). I interpret this data as a manifestation of the SNARC effect in motor magnitudes. To my knowledge, it is a novel effect that was not yet described in the literature.

The difference in the findings between Studies 3A and 3B is most likely due to the introduction of lateralized responses as it was the one variable that was changed. With this, we succeeded in activating explicit spatial processing displayed as the typical SNARC effect (Dehaene et al., 1993). The explicit spatial processing also completely modified the responses to number magnitudes displayed in motor magnitudes. Therefore, I interpret the effect as that of explicit spatial processing based on the semantic concept of ordinality represented independently from the GMS (Sixtus et al., 2023). Based on difficulty (model three) and not on ATOM (Walsh, 2003; 2015), number magnitudes then manifested in motor magnitudes due to explicit spatial processing.

Comparing the different results of Study 3A to 3B leaves the question of why number magnitudes affected motor magnitudes only during explicit spatial processing. This result is in direct contrast to Study 2 which did not have spatial information and yet found ATOM-like effects (Walsh, 2003; 2015) between number magnitudes and motor magnitudes. As above, I speculate that the timing of magnitude processing is crucial and can be utilized differently depending on the task. For instance, earlier magnitude activation that is based on classifying against the reference point (455ms; Study 3B) is sufficient to elicit magnitude processing under explicit spatial processing conditions. Such an early manifestation is then displayed according to the proposed model three. It is possible that this classification was not due to "real" magnitude activation but was performed based on ordinality alone (Pitt & Casasanto, 2019). However, this was certainly not the case in Study 2 in which the task enabled a later magnitude activation that was necessary to manifest as ATOM-like effects (starting earliest at 767ms; Study 2).

To conclude, the results of Studies 3A and 3B showed that number magnitude affected motor magnitudes only during the assessment of the SNARC effect in active responses. The reported interaction effect showing in motor magnitudes is likely due to SNARC-compatible and easier responses, and non-compatible and more difficult responses. Considering the timing of magnitude processing it is likely that magnitude processing does not occur at one point but has at least two stages of semantic processing. It is possible that the early stage is activated in tasks that require classifications while the later stage enables ATOM-like processing. I will consider this possibility in more detail in the discussion in Chapter 9.

Chapter 9: General Discussion

9.1 Summary of Findings

In the theoretical Part I of this Thesis I introduced ATOM and the GMS and described the within-magnitude dimensions (Walsh, 2003, 2015). I attempted to bridge the theoretical gaps of ATOM by connecting it to the embodied cognition framework (Barsalou, 2008; M. H. Fischer & Zwaan, 2008; Matheson & Barsalou, 2018; Raab, 2021). For this, I described how the embodied cognition framework can contribute to the precision of ATOM by specifying the mechanisms under which the GMS develops. I also specified points of critical difference between both by arguing how specific actions of finger use contribute to the development of the GMS as well as another form of an independent spatial representation (Sixtus et al., 2023). I also described the qualitative differences between grounded and embodied cognition based on the grounded-embodied taxonomy (Borghi et al., 2023; M. H. Fischer, 2012) and linked them to ATOM. The connections and differences between ATOM and grounded-embodied cognition are important for the empirical results described in this Thesis as they suggest that numerical magnitude and spatial processing rely on different representational mechanisms. The theoretical predictions and effect directions were based on ATOM (Walsh, 2003, 2015). The main hypothesis was that smaller number magnitudes should induce smaller motor magnitudes compared to larger number magnitudes. Additionally, I described experimental tests comparing the predictions of ATOM to the notion of an independent spatial processing based on ordinality (Sixtus et al., 2023).

The main empirical findings of this Thesis are:

Numbers and Force

1. Number magnitude has a direct effect on motor magnitudes during passive grip force readings. Smaller numbers induce smaller motor magnitudes while larger numbers induce larger motor magnitudes. (**Study 2**).
2. Number magnitude has no direct effect on motor magnitudes during passive directional isometric force recordings (**Study 1**).
3. Number magnitude has no direct effect on motor magnitudes during active responses (**Study 3A**).
4. Number magnitude has a direct effect on motor magnitudes during active responses that are carried out in lateralized response space (**Study 3B**).
5. Continuous spatial conditions have no direct effect on magnitude processing during number generation (**Study 1**).

Based on these results, I draw two major conclusions. First, there is a direct coupling between number magnitudes and motor magnitudes during passive grip force readings in the predicted direction made by ATOM. Second, spatial and active responses interact with number magnitudes displayed in motor magnitudes that challenge the predictions of ATOM. In addition, continuous spatial conditions failed to interact with number magnitudes which also challenged the predictions of ATOM. In the following, I will discuss the findings considering ATOM, grounded, and embodied cognition. I will follow up by describing the scientific relevance of this Thesis for basic research, continue with the quantification and specification of the effects, and then conclude the general discussion with the limitations of this project.

9.2 Present Results in the Light of ATOM, Grounded, and Embodied Cognition

In the introduction of this Thesis, I have described ATOM (Walsh, 2003, 2015) sharing Walsh's amazement in wondering what a "smart thing like number" (Walsh, 2015, p. 552) was doing in a brain area associated with automatic motor processing. Intriguingly, even though Walsh explicitly links numbers and automatic motor processing, no study has investigated a direct coupling between numbers and automatic motor processing before.

To motivate my own interest in this research project, I described the state of the art of prototypical experiments and experimental effects that can be interpreted in light of ATOM (**Chapter 4**). At the same time, I also described how other theories can also explain such effects (the polarity-correspondence account by Proctor & Cho, 2006; Proctor & Xiong, 2015; and the verbal-spatial account by Gevers et al., 2010; **Chapter 1**). I continued to describe a newer method of continuous force recordings and proposed how it can shift the explanatory power in favor of ATOM by quantifying rather than classifying behavioral measures. With this method, we were capable of testing spontaneous motor processing as it required no active responses. Relying on this method, in **Study 2** we reported number-force magnitude associations showing a direct coupling between semantic magnitude processing and motor magnitudes in the direction predicted by ATOM. Smaller numbers induced smaller motor magnitudes than larger numbers during spontaneous grip force recordings. These results extend previous literature that showed how more concrete representations of magnitudes such as numerosity, weight, and physical size affected motor magnitudes (Krause et al., 2019). While the study of Krause et al. (2019) depicted a within-magnitude association between multiple dimensions so early during childhood, the results of our **Study 2** extended it to semantic numerical magnitudes processing. In this case, semantic numerical magnitudes (precise magnitudes) are likely to have origins in continuous visual and motor magnitudes (Sixtus et al., 2023). Together, our study and the study by Krause et al. (2019) show that the understanding of magnitude is already present in early childhood and likely provides the ground for semantic magnitude knowledge. Therefore and according to the grounded-embodied taxonomy (Borghi et al., 2023; M. H. Fischer, 2012; see **Chapter 3**), magnitudes are likely *grounded* in the GMS. In addition, semantic numerical magnitudes are built upon these magnitudes and are further *embodied* through the GMS by sensorimotor experiences such as finger counting and gesturing (Sixtus et al., 2023). This view is also in line with **Article 1** in which we proposed how finger use contributes to the embodied nature of numerical cognition. Therefore, the results of **Study 2** add to the embodied cognition framework that postulates that semantic concepts (e.g., numbers) are built upon basic sensorimotor experiences (e.g., visual and motor magnitudes; (Barsalou, 2008; M. H. Fischer & Zwaan, 2008; Lindemann & Fischer, 2015; Matheson & Barsalou, 2018; Muraki et al., 2023; Raab, 2021).

However, this is not the full picture as number-force magnitude associations were absent in **Study 1**. It is possible that we did not find the effect due to the length of the measured time windows. In **Study 2** we found that semantic numerical processing affects motor magnitudes earliest starting at 767ms (801ms in Krause et al. 2019). However, in **Study 1** we were only able to analyze the time windows until 576ms because it marked the average voice onset of a generated number. We could not go beyond the 576ms mark as the voice onset produced motor artefacts affecting and contaminating force production. Therefore, our analyzed time windows were just not long enough to detect any effects of magnitude processing that are likely to occur in later stages of conceptual processing, if there were any.

Additionally, **Studies 3A and 3B** further specify under which conditions number magnitude affects motor magnitudes during active responses. The results of **Study 3A** indicated no relation between number and motor magnitudes during active responses that speak against the predictions of ATOM and our own findings in **Study 2**. Additionally, **Study 3B** showed a SNARC effect (Dehaene et al., 1993) in the reaction time data that Walsh interprets as evidence for ATOM (Walsh, 2003). However, our force data did not reveal an effect direction that could be interpreted in favor of ATOM. Compared to **Study 3A**, **Study 3B** shows how number magnitudes only affected motor magnitudes under conditions of explicit spatial processing. The interaction suggests a moderating role of the ordinal spatial processing (left/right) on motor magnitude during number magnitude processing. I interpreted the interaction as the manifestation of the SNARC effect in motor magnitudes based on the difficulty of incompatible responses. Smaller numbers were not compatible with the SNARC effect in the right space and produced larger motor magnitudes. In addition, larger numbers were not compatible with the SNARC effect in the left space and produced larger motor magnitudes (see Figure 6 in **Chapter 8**). For the field of numerical cognition, these findings could mean that the SNARC effect (Dehaene et al., 1993) might not represent evidence in favor of ATOM. Instead, it represents an effect of an independent processing mechanism specialized in processing ordinality as suggested by Sixtus et al. (2023). If the GMS links numbers with space producing the SNARC effect, why would it not simultaneously link smaller numbers with smaller motor force and larger numbers with larger motor force independent from space? I speculate that the reason is the described independence of the GMS with another spatial processing mechanism based on ordinality as explained above (also see Casasanto & Pitt, 2019; Pitt & Casasanto, 2019; Winter et al., 2015).

In an extension to the above argument, our findings point to a qualitative difference in magnitude processing between **Studies 2 and 3B**. Earlier I described how precise magnitudes (numbers) could also be based on continuous magnitudes (Sixtus et al., 2023). However, there seem to be two possible ways in which precise magnitudes could be processed. First, they can access the magnitude representation that is processed by the GMS (Walsh, 2003, 2015) as we described in **Study 2**. Second, when there are spatial task demands based on ordering, the representation of ordinality overrules the representation of magnitude leading to spatial numerical associations (**Study 3B**). Indeed, it is suggested that the magnitude classification task that is supposed to activate magnitude processing can be performed based on ordinal information alone (Pitt & Casasanto, 2019). This interpretation could mean that the concept of ordinality, at least during task demands as in typical SNARC-like experiments (Macnamara et al., 2018), is “stronger” than the representation of magnitude (in the taxonomy of grounded-embodied cognition; Borghi et al., 2023; M. H. Fischer, 2012). This could also potentially explain why our continuous spatial conditions in **Study 1** failed to affect number generation as they did not involve ordinal information and explicit spatial processing.

Together, these findings lead to several speculations regarding my interpretations expressed in this and the next paragraph. Based on Casasanto and Pitt (2019), I think that explicit spatial processing that produces SNARC-like effects (Macnamara et al., 2018) could be based on metathetic and qualitative variations rather than continuous and prothetic within-magnitude dimensions (Stevens, 1957). I speculate that the “left” and the “right space” are qualitative labels produced by explicit spatial processing that do not represent an amount of space. “Left space” is not less space and “right space” is not “more space”. Notably, this argument might not hold for the vertical axis where “higher space” could also mean “more space” than “lower space”. While there are no “left” and “right numbers”, there are “high” and “low numbers” indicated by universal metaphors such as “more is up” (Lakoff & Johnson, 1980; Lakoff & Núñez, 2000). Therefore, metathetic dimensions should not be processed by the GMS (Walsh, 2003, 2015) which is the common processing mechanism exclusively for prothetic dimensions described earlier. This could be the reason why the horizontal SNARC effect (Dehaene et al., 1993) is much less stable or absent in studies that do not utilize such labels in form of instructions, lateral responses, or other explicit lateral information (**Study 2**; Pinto, Pellegrino, Lasaponara, et al., 2019, 2021; Pinto, Pellegrino, Marson, et al., 2019, 2021; Shaki & Fischer, 2018).

I further speculate that the above-described metathetic and prothetic dimensions could be processed differently on the temporal continuum. Our current results show that magnitude processing during magnitude classifications (**Studies 3A/3B**) occurs within 487/455ms, respectively (grand mean of 632ms from the meta-analysis by Wood et al., 2008). These classifications are made according to the reference point five (smaller than 5 vs. larger than 5). When such a magnitude processing is combined with lateral responses (left vs. right) we find a SNARC effect that is expressed also in the force data (**Study 3B**). However, when there are no such classifications in the task, no lateral responses, and no time pressure to initiate an active response, then the magnitude-related onset starts only after 767ms (**Study 2**). Earlier I speculated that these results point to faster access to ordinal than to magnitude information during such different tasks.

For the field of numerical cognition, our findings would provide evidence towards the notion that the horizontal SNARC effect (Dehaene et al., 1993; smaller numbers are associated to the left of larger numbers) is a learned association based on ordinality. Indeed, cultural and individual learning histories such as reading and writing direction (Dehaene et al., 1993) and finger counting habits have been suggested for shaping it (M. H. Fischer, 2008; M. H. Fischer & Brugger, 2011; Lindemann et al., 2011). In addition, I interpret it as an independence of the semantic concepts of magnitude and ordinality as proposed by the sensorimotor perspective on numerical cognition (Sixtus et al., 2023). In the grounded-embodied cognition taxonomy (Borghi et al., 2023; M. H. Fischer, 2012), this could be interpreted as an *embodied nature of ordinality* (possibly through finger counting (M. H. Fischer, 2008; M. H. Fischer & Brugger, 2011; Sixtus et al., 2023) that overrules *the grounded nature of magnitudes* in specific conditions that require explicit spatial processing.

In conclusion, **Study 2** supports the prediction of ATOM and shows a direct coupling between numbers and motor magnitudes. It also supports the proposition that precise numerical magnitudes are *embodied* by fingers *and grounded* in continuous magnitudes. In addition, **Studies 3A and 3B** show a moderating role of ordinal space in magnitude processing. The spatial task demands in **Study 3B** were likely to activate spatial numerical associations and the concept of ordinality. The findings contribute to the proposal that there exists an independence between the semantic concepts of magnitude and ordinality. This independence points to a different *grounding and embodied* mechanisms of conceptual knowledge represented in either the GMS or spatial ordering mechanisms.

9.3 Scientific Relevance

In this Chapter, I aim to propose how we can advance theory and resolve some of the issues I described in the last Chapter by utilizing continuous force recordings (see **Chapter 4**). This concerns research disciplines interested in spatial effects, disciplines interested in testing ATOM (Walsh, 2003, 2015), disciplines that aim to measure effects within the embodied cognition framework, and disciplines utilizing the reaction times paradigm. For this, I will start by describing why space does not necessarily equal space (Casasanto & Pitt, 2019) by interpreting previous literature and the findings of our own empirical work.

Consider what magnitude means and how we acquire the semantic understanding of magnitudes. The semantic concept of magnitude is likely based on continuous amounts (Leibovich et al., 2017; Sixtus et al., 2023) and ATOM proposes that the GMS is the common processing mechanism for magnitudes (Walsh, 2003, 2015). Sensorimotor experiences help acquire the understanding of magnitudes through interactions with discrete and continuous amounts (for integration of sensorimotor experiences into the framework of Leibovich et al., 2017 see Rinaldi and Girelli, 2017). For instance, while counting the number of bees in a picture, the child can use their fingers to represent the single bees. Counting more bees will proportionally increase the total area the fingers occupy. Additionally, the child also scans the picture with its eyes and more bees are likely to occupy a larger area that also requires more oculomotor involvement (e.g., Gandini et al., 2008). Overall, the statistical learning of magnitudes is often accompanied by movements that produce and/or occupy larger space. For instance, visual scanning of larger areas will require more oculomotor involvement than that of smaller areas (Gandini et al., 2008), gestures representing larger sets will occupy more visual space than that of smaller sets (Sixtus et al., 2023), and larger foods initiate a larger mouth opening than smaller foods (Gentilucci et al., 2001). Therefore, magnitude and space are two within-magnitude dimensions that are deeply intertwined. In the following, I aim to make the argument that the state of art and mental chronometry might not capture this view with their prototypical experiments depicting the magnitude-spatial associations.

The SNARC (Dehaene et al., 1993) and SNARC-like effects have inspired a large area of research systematically investigating the relationship of magnitude-spatial associations of response codes (Macnamara et al., 2018). In these experiments, there is usually some sort of stimuli (e.g., numerical, temporal, musical, size) that is to be classified either based on its magnitude (explicit condition) or a different categorization in which the magnitude is irrelevant (implicit condition). The classifications are given as lateral responses on the left vs. right response space (responses on the vertical and sagittal axes are also possible, but irrelevant to this argument). The typical result usually depicts smaller magnitudes to the left of larger magnitudes. ATOM is not the only theory capable of explaining such effects as the polarity-correspondence (Proctor & Cho, 2006; Proctor & Xiong, 2015) and the verbal-spatial coding (Gevers et al., 2010) accounts are also capable of explaining the magnitude-spatial associations based on stimulus-response compatibility. Critically, and as described in the previous **Chapters 1.1, 4.1,** and **9.2**, many (if not all) of such magnitude-spatial associations of response codes studies (Macnamara et al., 2018) might actually be accessed based on their metathetic and qualitative variations instead of prothetic (Stevens, 1957) and continuous within-magnitude dimensions processed by the GMS (Walsh, 2003). I think that this distinction is important. While Sixtus et al. (2023) emphasize the independent existence of the semantic concepts of magnitude and ordinality (and cardinality) the authors still depicted bi-directional arrows between the GMS and the spatial ordering account which does not eliminate dependencies. According to my interpretation (that is rather radical) and to make predictions even more precise both should be *fully* independent.

Consider **Study 3B** in which we utilized the magnitude classification task that required classifying numbers as “smaller” or “larger than five” by responding in either the left or right response space. The study had two blocks with a counterbalanced response mapping with either small/left vs. large/right (SNARC compatible) or small/right vs. large/left (SNARC incompatible). We found that smaller numbers produced smaller motor magnitudes in the left response space while larger numbers also produced smaller motor magnitudes in the right response space (and vice versa; see Figure 6; Dehaene et al. 1993). Now consider another study that also used the magnitude classification task that required classifying numbers as smaller or larger by giving a verbal response (Miklashevsky et al., 2022). Critically, the response was given to either the smaller or the larger number based on the experimental block. In one block the participants responded only to smaller numbers and in the other block only to larger numbers. Responses were measured excluding response codes by bimanual passive grip force recordings that did not require active responses (similar to **Study 2**). Instead, that study measured the balance of force between both hands during the numerical task. In that study, smaller numbers induced larger motor magnitudes in the left hand while larger numbers induced larger motor magnitudes in the right hand (Miklashevsky et al. 2022 in Experiment 2 during the time window between 180 and 400ms). Both of the described experiments have interpreted the results in favor of the typical horizontal spatial numerical associations. Both experiments also reported opposite results regarding motor magnitudes. I interpret these contrasting results as a qualitative difference of spatial information being either discrete and ordinal or continuous. **Study 3B** induced discrete and ordinal information based on explicit task instructions and the classification of number magnitudes in response codes. In the other study (Miklashevsky et al., 2022) there were no explicit task instructions on how to classify number magnitudes in the left and right response space. I think that this approach could have induced continuous spatial within-magnitude information by leaving out the explicit spatial processing of ordinal classification of left and right. If my speculation is correct, then previous research utilizing response codes cannot count as direct evidence for within-magnitude processing between magnitudes and space. Instead, they should be interpreted as magnitude associations within a spatial order based on metathetic and qualitative dimensions. Future research could try and disentangle continuous and ordinal space representations. This could further lead to theory development (grounded and embodied cognition) and shed light on how exactly and under which conditions we process “which” space. At the very least, the field of numerical cognition as well as ATOM can recognize the dimension of motor force as a prothetic dimension (driven by results of **Study 2** and Krause et al., 2019; Miklashevsky et al., 2022; but not on Krause et al., 2014; Vierck & Kiesel, 2010 which I think are based on metathetic variations as argued in **Chapter 4**) that can enable further research.

Overall, force recordings such as grip force can substantially expand previous experimental effects described in the literature. It provides a new method capable of measuring magnitude processing as a direct coupling to motor magnitudes. With continuous grip force recordings, we now have a method to measure continuous amounts during the assessment of behavior while maintaining high experimental control due to a laboratory setting. Being a continuous method, we have now access to full force profiles that depict the sum of cognitive processing. Based on the previous discussion of this Thesis, I think that basic research utilizing this method could potentially challenge old findings (metathetic vs. prothetic), extend old findings (force display in spatial tasks), and create new ones (number-force magnitude associations). To conclude, methodological advancement goes hand in hand with theoretical advancements by enabling the testing of new effects and putting old effects into a new perspective.

9.4. Quantification and Specification of Found Effects

9.4.1 Quantification

Meaningfully quantifying the effects of our studies is a difficult, if not impossible, endeavor. This is due to the combination of novel factors applied in our studies. For instance, while there exists plenty of literature that tested SNARC and SNARC-like effects (Dehaene et al., 1993; Macnamara et al., 2018; Wood et al., 2008) only some measured force as the dependent variable in any numerical context. However, in order to quantify the effect sizes reliably, studies with the same research question and comparable conditions need to accumulate (Field & Gillett, 2010). Therefore, this quantification section is rather limited in evidence.

Indeed, the literature assessing number-force magnitude associations is scarce. To my knowledge, only three other studies have assessed how number magnitudes affect motor magnitudes measuring force production. Two of these studies have also not found number-force magnitude associations measuring motor magnitudes (R. Fischer & Miller, 2008; Miklashevsky et al., 2021). The other study reported number-force magnitude associations only as a side effect while assessing a hypothesis based on the mental number line (Miklashevsky et al., 2022). Additionally, the only study reporting how magnitudes affect motor magnitudes utilized perceived magnitudes (Krause et al., 2019). Overall and given that the finding of **Study 2** was not just a random artifact and can be replicated in the future, the reported effect is a new addition to the literature. We were able to quantify the effect during action execution and establish it as an embodied effect.

I argue that our novel methodology of measuring continuous and isometric grip force is the reason why we were able to detect number-force magnitude associations. This is because I think that the effect is rather small and needs sensitive methods and appropriate experimental designs to be detected. For **Study 2**, we conducted a sensitivity power analysis (post-hoc) with a sample size of 43 participants, an alpha= 0.5, and a probability of (1-beta)= 0.8 for a two-tailed one-sample t-test (G*Power 3.1; Erdfelder et al., 2009). The test concluded that we were able to find an effect with a medium to large effect size (d'= 0.44). Given our study was among the first ones showing a number magnitude and motor magnitude coupling while also utilizing a novel method, I think this is an overestimation of the true effect size. It remains to be seen if and under which conditions the effect can be replicated. As we have seen from **Study 3A**, the combination of the magnitude classification task with active responses is not suitable.

I draw this conclusion based on two major findings in and outside our own empirical work. First, long trials are essential for numerical magnitudes to be fully processed. Whenever the effect is measured before 767ms it does not occur (based on short time windows see **Study 1**, for fast reactions see **Study 3A** and Krause et al., 2014; Vierck & Kiesel, 2010; but see Miklashevsky et al. 2022 for an onset starting at 500ms). Second, whenever there is spatial information in a study, unforeseen interactions between magnitudes and response space might occur and the effect is either not found (R. Fischer & Miller, 2008; Miklashevsky et al., 2021) or altered (**Study 3B** and Miklashevsky et al., 2022). This brings me to my second point: **Study 3B** showed how the SNARC effect interacts with motor magnitudes during active responses. **Study 3B** conceptually replicated the SNARC effect measuring reaction times (Dehaene et al., 1993). However, a new addition to the well-known SNARC effect is that it also has a signature expressed in motor magnitudes. Such findings could have potential theoretical implications that I discussed in detail earlier (**Chapters 9.1 9.2,** and **9.3**).

9.4.1 Specification

In addition to quantification, in **Table 2** I specified the boundary conditions under which we can and cannot expect number magnitudes to affect motor magnitudes. For this, I have summarized experimental studies within and outside this Thesis that measure motor magnitudes with and/or without spatial information. I think it contributes to the overarching discussion to report the full experimental design space for easy comparison between experiments and their designs (Almaatouq et al., 2022). Future studies can utilize this table to replicate and extend older findings or systematically test boundary conditions of effects (as in **Studies 3A** vs. **3B** or **3B** vs. Miklashevsky et al. 2023).

In the table, I listed magnitude processing, response types, response space, spatial processing, and the reported effects of relevant studies. I chose these factors as they are omnipresent in numerical cognition studies (at least the studies described in this Thesis). They are essential to differentiate as the combination of these factors can access very different cognitive processes (e.g., continuous spatial processing vs. explicit spatial processing or effects based on grounded cognition vs. embodied cognition).

Magnitude processing relates to the cognitive tasks in the studies and is classified in terms of the conceptual activation being either explicit or implicit. For instance, the magnitude classification task's primary goal is to activate magnitude processing that is categorized as explicit (for counterevidence see Pitt & Casasanto, 2019). The parity classification task's primary goal is to activate the parity of the numbers (odd/even) making magnitude processing implicit as numbers can automatically activate their semantic magnitudes (Dehaene et al., 1993); for counterevidence see Namdar et al., 2018). The 1-back number comparison task (**Study 2**) assumes explicit magnitude activation as number magnitude is needed to fulfil the task. For the RNG task, magnitude processing can be classified as explicit as there are instructions that specify the range in which numbers need to be produced. These instructions need to be checked if the produced numbers are acceptable within the instructed range (Shaki & Fischer, 2018). Finally, the task utilized by Krause et al. (2019) is difficult to classify as it utilized visual magnitudes that could have activated multiple conceptual representations of within-magnitude dimensions such as numerosity, weight, and physical size. Additionally, there might have been some interaction with the spatial direction "up" as stimuli moved upwards.

The categorization of response types is based on active responses that require an action such as a button press while passive recordings are produced without active responses (e.g., **Studies 3A/B** vs. **Studies 1/2**, respectively). Response space categorizes whether the responses were centrally aligned to the stimulus presentation on the horizontal axis (e.g., **Studies 1**, **2**, and **3A**) or were laterally placed in the left and the right response space (**Study 3B**).

Spatial processing refers to whether explicit spatial processing was activated during the task. For instance, when there was a classification task and lateralized responses, spatial activation was marked because it was relevant to fulfil the task. The column “effects” summarizes the findings of the experiments as no findings, findings as predicted by ATOM (Walsh, 2003, 2015), findings of spatial numerical associations (based on the mental number line; (Restle, 1970), findings of the FoNARC effect (Krause et al., 2014; Vierck & Kiesel, 2010), and others such as difficulty (e.g., **Study 3B**). Finally, **Study 1** relied on verbal random number generation while all other studies utilized visually presented stimuli that were presented centrally on a screen.

Table 2

Overview of the experimental studies that measured motor magnitudes with and without spatial information.

Experiments	Task	Magnitude processing		Response type		Response space		Spatial processing	Effects	
		Explicit	Implicit	Active	Passive	Centralized	Lateralized		Motor magnitudes	Reaction times
Study 2	1-back comparisons	x			Constant and continuous grip force	x			ATOM	
Krause et. al. 2019	Visual magnitudes	x		Single button		x		Task irrelevant Items moved up automatically	ATOM	
Study 3A	Magnitude classifications	x		Pressing on a solid sensor. No yield		x			no	no
Krause et al. (2014) Non-spatial task	Parity classifications		x	Single button. No yield		x			no	FoNARC
Vierck & Kiesel (2010)	Parity classifications		x	Single button		x			no	FoNARC
R. Fischer & Miller (2008)	Parity classifications (Experiment 1)		x	Buttons			Contrasts left/right	x	no	SNARC
R. Fischer & Miller (2008)	Magnitude classifications (Experiment 1)	x		Buttons			Contrasts left/right	x	no	SNARC

Miklashevsky et al .(2022) Experiment 2	Magnitude classifications	x			Constant and continuous grip force		Lateralized but no explicit contrasts between left/right	x	SNAs (180-400ms) ATOM (500-1750ms)	
Study 3B	Magnitude classifications	x		Pressing on two solid sensors. No yield			Contrasts left/right	x	Motor magnitudes as an **interaction** between number magnitude and ordinal space	SNARC
Study 1	RNG	x			Constant and continuous force	Centralized but directional	No contrasts		no	

Note. This table provides an overview of studies that measured motor magnitudes while assessing associations between number magnitude and motor magnitudes and/or number magnitude and space within a single experiment. The acronyms listed in the table stand for Random Number Generation (RNG; Shaki & Fischer, 2014), A Theory of Magnitude (ATOM; Walsh, 2003, 2015), Force Numerical Associations (FoNARC; Krause et al., 2014; Vierck & Kiesel, 2010), Spatial Numerical Associations (SNARC; Dehaene et al., 1993), and Spatial Numerical Association (SNAs).

9.5 General Limitations

9.5.1 Limitations in the Experimental Strategy

In **Chapter 5** (also see Figure 1) I described the experimental strategy of this research project. Overall, the experimental strategy involved many levels of design choice. Some of these choices were made to completely overhaul previous designs (**Study 1 → Study 2**). Others intended to contrast the designs (**Study 1 → Study 3B**). Others were made to extend the findings from previous studies to another method (**Study 2 → Study 3A**). Finally, others were made to enable a direct comparison between the two study designs by changing only one factor (**Study 3A → Study 3B**). While such different design choices were justified, it also means that some interpretations were based on assumptions. For instance, **Study 3A** was designed to conceptually replicate **Study 2** by extending the findings to active responses. However, simultaneously we also changed the task so **Study 3A** could be directly comparable to **Study 3B**. As we found no effects in **Study 3A**, we cannot be sure if that was due to the new task or the new response type. Similar was the case between **Studies 1 and 2** which utilized different tasks, and response types, and either included or excluded spatial conditions. Overall, only **Studies 3A and 3B** are directly comparable that results in strong interpretations of the findings. Therefore, whenever I compared studies with each other, there was a certain level of assumptions involved. A good example of this is the comparison of **Studies 1 and 2** (see **Chapter 9.2**). There I argued that it is likely that we did not find any effects of a direct coupling between number magnitudes and motor magnitudes because of the short time windows of **Study 1**. However, the two studies also utilized very different tasks based on visual perception vs. verbal production and different response types of directional force vs. grip force. In conclusion, some of my interpretations of and between the studies involved a certain level of assumptions that implied a general transfer between "stuff".

9.5.2 Limitations of the Theoretical Interpretations

I think that my Thesis has a strong theoretical background. Also, some of my theoretical interpretations were made in hindsight. For instance, the interpretation and the motivation of **Study 3B** were based on the theoretical ground that the semantic concept of ordinality shapes spatial ordering that is independent of the GMS (Sixtus et al., 2023). Therefore, exploring how such explicit spatial processing affected motor magnitudes was intriguing. However, at the time when we constructed the study, I was not aware of this theoretical distinction. For a while I had a "feeling" that spatial ordering does not necessarily mean continuous space. In my thinking, the continuous spatial conditions (**Study 1**) were incomparable to the experiments that utilized explicit spatial processing (as in **Study 3B**; for a meta-analysis of such experiments see Macnamara et al., 2018). In conclusion, I display a strong confirmation bias in many of my arguments after reading the paper by Sixtus et al. (2023).

9.5.3 Limitations of the Methodology

In **Chapter 4** I described the rather novel method of continuous force recordings that we used in this research project. As this method is rather novel it comes with certain limitations. There is only one methodological paper describing how the force sensors should be used (Nazir et al., 2017). However, this study describes only how to use them as grip force sensors and only during linguistic experiments. There are no instructions on how to use it for other cognitive processes such as the processing of number magnitudes. However, this is critical as cognitive processes might differ in how they manifest in grip force. This can be due to their "strength", the timings, involvement with other cognitive processes etc. There are also no instructions on how to use it as another response type such as directional force (**Study 1**) or as an imitation of a button (**Studies 3A** and **3B**). One of the biggest challenges of this research project was to estimate what the best pre-processing procedures were as they vary between response types and the length of the measured time windows. This could also be the reason why the reported grand means of the reaction times in **Studies 3A** and **3B** deviate from the grand means reported with real buttons (for magnitude classifications see 487/455ms in **Studies 3A/3B** vs. 632ms from the meta-analysis by Wood et al., 2008). Ideally, the pre-processing procedures and the statistical analyses should be specified a priory in order to enable confirmatory analyses. However, at the current level of knowledge of the field, this is hard to achieve. This is especially true when response types are switched from continuous grip force (**Study 2**) to continuous force (**Study 3A**; unanalyzed NoGo trials), to directional force (**Study 1**), and to active responses (**Studies 3A** and **3B**). Overall, continuous force recordings are very rich in information as they provide insight into what happens during cognitive processing and at the motor control level. It is an extension to the finding how quantifying motor magnitudes during response execution provides additional knowledge on what happens after a response is made (Balota & Abrams, 1995). However, the field needs more knowledge on how to analyze and pre-process the data collected during continuous force recordings.

Finally, I interpret the data from continuous grip force recordings as simulation processes that are spillovers from the motor cortex (see Chatterjee, 2010; Goldman, 2012). Such an interpretation is in line with the embodied theories that assume that conceptual knowledge retrieval is accompanied by obligatory activations of the sensorimotor system (Barsalou, 2008; also see M. H. Fischer, 2012; Muraki et al., 2023; Raab, 2021). However, while the grip force profiles depict forces on a temporal continuum, it is a black box. We do not know what exact processes cause these grip force fluctuations. Future studies could combine continuous grip force recordings with other continuous methods (skin conductance, respiration, for electroencephalography see Pérez-Gay Juárez et al., 2019) to systematically validate each other. They also could be deployed in studies utilizing transcranial magnetic stimulation. Let us explore what happens to the grip force profiles when we disable the motor cortex! It would be fascinating to find effects depicted in the grip forces while the motor cortex is inhibited or activated.

Chapter 10: Conclusion

The present Thesis aimed to provide some theoretical answers on what numbers do within one of the motor processing area of the brain and empirical findings on how it affects behavior. I have explored A Theory of Magnitude and the General Magnitude System and theorized how Grounded and Embodied Cognition can further specify the mechanisms of how magnitudes and numbers are mentally represented. The unique contribution of this Thesis is that I showed a direct coupling of numerical magnitudes and motor magnitudes during semantic numerical magnitude processing. In other words, I showed how numbers affect behavior without our awareness. This finding suggests that there is a common processing mechanism of magnitudes as proposed by A Theory of Magnitude. This finding also suggests that the more abstract concepts such as a number are directly embodied in sensorimotor experiences. In addition, I also showed how replicating established effects with a novel method can shed new light on these established effects and challenge their theoretical interpretations.

In conclusion, the current research adds evidence to the proposal suggesting an *embodied nature of numbers* that are embodied in sensorimotor experiences and based on *grounded magnitudes*.

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Note. These references are only for Chapters 1,3,4,5,8,9, and 10.

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List of Tables

Note. There are multiple Tables with the same name as the formatting of the published studies was kept. Therefore, I indicated in square brackets the Appendix number in which the Table was presented. For instance, Table 1 form Appendix 2 will be referred to as Table 1[A2]. Tables within this Thesis are stand-alone and will not get these attachments. **Treat the manuscript of Study 1 as Appendix 2.**

List of Figures

Note. There are multiple Figures with the same name as the formatting of the published studies was kept. Therefore, I indicated in square brackets the Appendix number in which the Figure was presented. For instance, Figure1 form Appendix 1 will be referred to as Figure 1[A1]. Figures within this Thesis are stand-alone and will not get these attachments. **Treat the manuscript of Article 1 as Appendix 1. Treat the manuscript of Study 1 as Appendix 2. The unpublished manuscript of Study 2 is inserted as Appendix 3.**

Appendix 1

Article 1

2.1. A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices

Published as:

Michirev, A., Musculus, L., & Raab, M. (2021). A Developmental Embodied Choice Perspective Explains the Development of Numerical Choices. *Frontiers in Psychology, 12*, https://doi.org/10.3389/fpsyg.2021.694750

Abstract:

The goal of this paper is to explore how an embodied view can redirect our understanding of decision making. To achieve this goal, we contribute a developmental embodied choice perspective. Our perspective integrates embodiment and bounded rationality from a developmental view in which the body provides cues that are used in abstract choices. Hereby, the cues evolve with the body that is not static and changes through development. To demonstrate the body's involvement in abstract choices, we will consider choices in numerical settings in which the body is not necessarily needed for the solution. For this, we consider the magnitude-judgment task in which one has to choose the larger of two magnitudes. In a nutshell, our perspective will pinpoint how the concept of embodied choices can explain the development of numerical choices.

Appendix 2

Study 1

6.1 How to not induce SNAs: The insufficiency of directional force

Published as:

Michirev, A., Kühne, K., Lindemann, O., Fischer, M. H., & Raab, M. (2023). How to not induce SNAs: The insufficiency of directional force. *PLoS ONE 18*(6): e0288038. https://doi.org/10.1371/journal.pone.0288038

Abstract:

People respond faster to smaller numbers in their left space and to larger numbers in their right space. Here we argue that movements in space contribute to the formation of spatial-numerical associations (SNAs). We studied the impact of continuous isometric forces along the horizontal or vertical cardinal axes on SNAs while participants performed random number production and arithmetic verification tasks. Our results suggest that such isometric directional force do not suffice to induce SNAs.

Appendix 3

Study 2

7.1 Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces

Submitted as:

Michirev, A., Lindemann, O., Kühne, K., Fischer, M.H., & Raab, M. (submitted). Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces.

Cognition

Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces

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Corresponding Author:	Alexej Michirev German Sport University Cologne Cologne, Nordrhein-Westfalen GERMANY
First Author:	Alexej Michirev
Order of Authors:	Alexej Michirev
	Oliver Lindemann
	Katharina Kühne
	Martin H. Fischer
	Markus Raab
Abstract:	This study investigated the relationship between semantic numerical magnitudes and motor magnitudes. For this, we recorded continuous grip force fluctuations from 43 healthy adults during a symbolic magnitude comparison task. We found that numbers induced spontaneous grip force fluctuations during number processing. Smaller numbers induced lower grip forces, whereas larger numbers induced larger forces. This result constitutes strong behavioral support for a generalized magnitude processing by continuously quantifying the response that challenges binary accounts of cross-domain interactions.
Suggested Reviewers:	Vincent Walsh v.walsh@ucl.ac.uk
	Mariagrazia Ranzini mariagrazia.ranzini@unipd.it
	Mauro Pesenti mauro.pesenti@uclouvain.be

Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces

Michirev, A.[1*#], Lindemann O.[2#], Kühne, K.[3], Fischer M.H[3]. & Raab, M[1].

1. Department of Performance Psychology, German Sport University Cologne, Cologne, Germany

2. Department of Psychology, Education and Child Studies Erasmus University Rotterdam Netherlands

3. Division of Cognitive Sciences, University of Potsdam, Potsdam, Germany

* Corresponding author

# These authors share the first authorship

Email: alex.michirev@outlook.com

Spontaneous Grip Force Fluctuations Mirror Semantic Numerical Magnitude Processing: Larger Numbers Elicit Larger Forces

ABSTRACT

This study investigated the relationship between semantic numerical magnitudes and motor magnitudes. For this, we recorded continuous grip force fluctuations from 43 healthy adults during a symbolic magnitude comparison task. We found that numbers induced spontaneous grip force fluctuations during number processing. Smaller numbers induced lower grip forces, whereas larger numbers induced larger forces. This result constitutes strong behavioral support for a generalized magnitude processing by continuously quantifying the response that challenges binary accounts of cross-domain interactions.

Total word count: 3788

Keywords: A Theory of Magnitude, magnitude congruency, numerical cognition, embodied cognition, grip force, continuous measurement

1. Introduction

Quantities of different dimensions are interconnected, and increases in one dimension are often associated with increases in others. When we pour water into our glass or pile up objects, their size increases, leading to universal metaphorical expressions such as “more is up” (Lakoff & Johnson, 1980; Lakoff & Núñez, 2000). These size associations also made it in the realm of symbolic numbers. For instance, a higher number is automatically associated with a physically larger number (and vice versa; Henik & Tzelgov, 1982). The cognitive relevance of such experiences was demonstrated in a classical study that manipulated the association between numerical and physical size of symbolic numbers and observed the Size Congruency Effect (Banks & Flora, 1977; Henik & Tzelgov, 1982). Whenever the two dimensions of a number symbol (its physical size and its meaning) are congruent they facilitate the response (e.g., the higher number also being the physically larger number: **9** - 1) and whenever they mismatch they interfere with the response (e.g., the lower number being the physically larger number: **1** - 9). Size congruency effects are not limited to the font size of numbers and also extend to other magnitude-related physical dimensions. For instance, increases in numerical magnitude also translate to lower luminance (Kadosh & Henik, 2006), larger luminance contrast (Gebuis & van der Smagt, 2011), longer lines (Dormal & Pesenti, 2007, 2009), longer duration (Dormal et al., 2008), larger dot sizes (Gebuis et al., 2009), and more weight (Charpentier, 1891).

In addition to such cross-dimensional interferences, numerical magnitudes also directly affect behavior. For instance, numerical magnitudes affect the selection of manual actions such as grasping movements and gestures. Indeed, participants select and initiate precision grip actions faster in response to small numbers and power grip actions in response to large numbers (Lindemann et al., 2007). Similar effects were found for the opening and closing of the hand (Andres et al., 2004). Together, the studies show that the processing of numerical magnitudes affects the selection of size-related motor features in manual actions.

Such cross-dimensional interferences provide evidence for parallel processing of magnitude-related dimensions. Indeed, A Theory of Magnitude (ATOM; Walsh, 2003, 2015) proposes one generalized magnitude system for prothetic within-magnitude dimensions (Stevens, 1957) in which “more” in one dimension automatically corresponds with “more” in another. The generalized magnitude system is believed to operate from birth; however, it is also shaped by sensorimotor interactions with the environment. Therefore, ATOM is in line with the idea of embodied cognition theories which highlight the importance of sensorimotor interactions to form conceptual knowledge (Barsalou, 2008; Raab, 2021), including numerical cognition (Fischer, 2012; Lakoff & Núñez, 2000; Lindemann & Fischer, 2015). As shown above, fine vs. coarse motor activities would typically be directed towards small vs. large objects, respectively; similarly, small and large object sets would typically be characterized with small and large number names, respectively.

We chose the embodiment cognition framework and the theoretical predictions of ATOM to provide evidence for within-magnitude associations beyond dichotomous associations described above. For this, we tested the within-magnitude association between number magnitudes and motor magnitudes by continuously quantifying instead of classifying the response. This approach is justified as other non-embodied theories could also potentially explain the dichotomous effects described above with stimulus-response based explanations. This is because dichotomous effects do not necessarily access prothetic and quantifiable within-magnitude dimensions (Stevens, 1957) but rather metathetic and qualitative variations (Casasanto & Pitt, 2019).

Such metathetic and qualitative variations occur whenever there are structural similarities between dimensions expressed by compatibility. Hereby, the dimensions can be coded in polar opposites (+/-) while compatibility is expressed by matching poles between these dimensions (the polarity-correspondence account; Proctor & Cho, 2006; Proctor & Xiong, 2015). When participants are asked to choose between weak vs. strong response-types to small vs. large numbers, they classify the response-types and numbers based on their compatibility. The compatibility is then displayed between “weak response-type and small number” and between “strong response-type and large number” (Krause et al., 2014; Vierck & Kiesel, 2010). However, when participants are asked to produce a response without any dichotomous instructions and this response is quantified in e.g. force, then the total produced force is weaker for a smaller number of objects and stronger for a larger number of objects (Krause et al., 2019). Such a quantification of a prothetic dimension rather than a metathetic classification directly challenges accounts based on stimulus-response compatibly (e.g., Proctor & Cho, 2006; Proctor & Xiong, 2015).

As shown from the above-presented examples, the general idea of within-magnitude associations between size and force is not new. For instance, while numbers and response-types were classified as “weak response-type and small number” and “strong response-type and large number”, the total produced force did not differ for small and large numbers (Krause et al., 2014; Vierck & Kiesel, 2010). In contrast, while the total produced force was weaker for a smaller number of objects and stronger for a larger number of objects; the within-magnitude dimension was not manipulated by number magnitudes (Krause et al., 2019). Rather, the authors reported how “perceived magnitudes” of numerosity, weight, and physical size affected force. The combination of all these within-magnitude dimensions into one stimulus makes it impossible to disentangle which specific within-magnitude dimension or whether their overall contribution was driving the effect. Additionally, the effect was found in toddlers (2-3 years of age). Therefore, extending such an effect to adults and semantic numerical processing would show direct evidence for an embodied nature of numbers.

Critically, no experiment has quantified motor force during semantic numerical magnitudes processing as a direct test of ATOM (Walsh, 2003, 2015). However, numbers were shown to affect motor magnitudes caused by spatial-numerical associations in adults. For instance, motivated by the mental number line hypothesis, Miklashevsky et al. (2022) demonstrated that numbers modulated the balance of grip force when holding objects in both hands. Smaller numbers led to a relative increase of the holding force in the left hand, while larger numbers increased the relative right-hand holding force. These effects in passive holding force were interpreted as spatial-numerical associations and the resulting priming of the left or right side of space (cf. Miklashevsky, 2022). However, it remains unclear whether the processing of small and large numerical magnitudes is directly associated with magnitude-related representation in motor actions.

In this study, we aimed to test a direct association between semantic numerical magnitudes and motor magnitudes. We ensured the independence from spatial numerical associations by removing task demands that are known to produce them and that were part of the Miklashevsky et al. (2022) study. These task demands are the contrasts of “smaller than five” vs. “larger than five” in the magnitude-classification task, as well as left vs. right response space (e.g., Pinto et al., 2019; for an overview see Michirev et al., 2023). In our study, we removed these contrasts in both the presentation and the response space, therefore, testing number-force magnitude associations instead of spatial numerical associations.

In line with ATOM (Walsh, 2003, 2015) and embodied numerical cognition, we predict that the processing of numerical magnitudes directly affects motor actions. We expect that processing numbers modulate the force of simultaneously performed manual actions, such as holding an object. That is when measuring spontaneous grip force fluctuations while number reading (cf. Miklashevsky et al. 2022), we expect larger motor force for larger compared to smaller numbers. Therefore, we aim to quantify motor force production during semantic numerical processing.

2. Method

We measured spontaneous grip force fluctuations in response to randomly presented numbers. We requested participants to hold a grip force sensor in their right hand and employed an n-back task (n=1; Sweet, 2011) with numerical comparisons. The 1-back task ensured semantic numerical processing as it required participants to hold each number in short-term memory until the next number was presented.

2.1 Participants

We tested 43 naive participants (20 females, mean age 24.3 years, range 19 - 44 years; 41 reported German, 1 Spanish, and 1 English as the first language) with normal or corrected-to-normal vision, no self-reported motoric diseases, and right-handedness. All participants were volunteers, signed the informed consent form, and were compensated. The experimental procedure was approved by the local ethics committee (approval number 21/2019) and conformed to the Declaration of Helsinki. One participant's data was not analyzed because of low accuracy (86.7%). Two participants had to be excluded from the grip force analysis because of excessive grip force fluctuations (see below). The resulting sample size was n= 40.

2.2 One-Back Task with Numerical Comparisons

We presented numbers for 1000ms followed by a visual mask again for 1000ms (see Fig. 2) to capture magnitude activation that had rather late onsets in previous studies (Krause et al., 2019; Miklashevsky et al., 2022).

Participants had to indicate in 16.7% of trials whether the currently presented number differed from the previously presented number by 1 or 2. Responses were given verbally (saying the German/English word for '*one'* or '*two'*) and were registered by the experimenter. In these catch trials, the number was red; in all other trials the number was white. A response to a catch trial was followed by an inter-trial interval of 1000ms and a fixation dot of 500ms before the next experimental trial started (see Fig. 1).

All numbers were centrally presented in sans-serif font using the open-source program OpenSesame (Mathôt et al., 2012). With an approximate viewing distance of 70 cm, the vertical visual angle was approximately 1.63°.

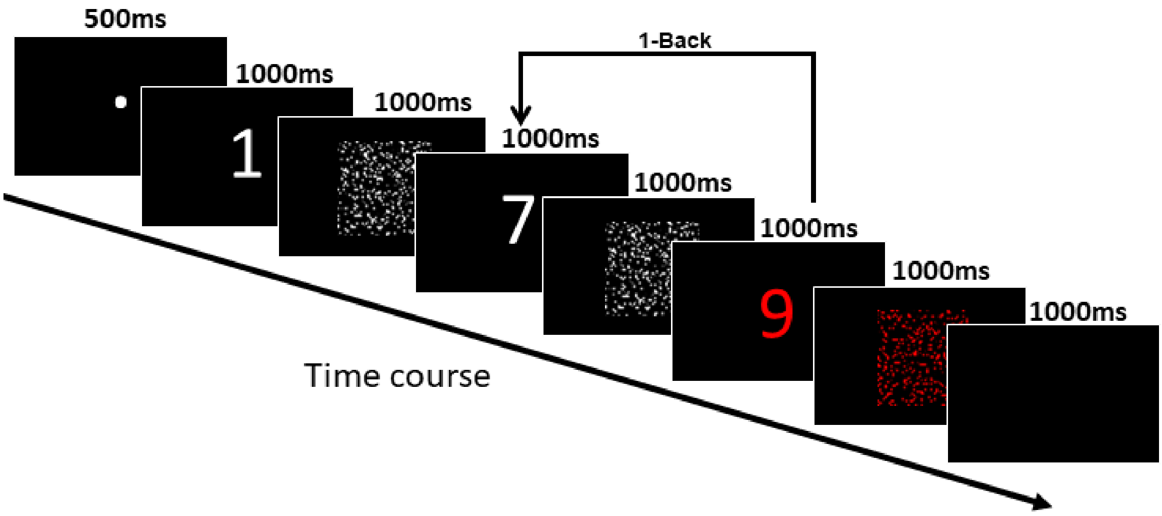

Fig. 1. Schematic overview of stimulus presentation and time course during the 1-back task.

2.3 Measurement of Spontaneous Grip Force Fluctuations

Participants held the grip force sensor in their right hand during the entire experiment. The hand position was fixed to be below the screen center and this was ensured by table markings. The sensor was a stand-alone load cell (ATI mini-40; see Fig. 2; ATI Industrial Automation, USA, www.ati-ia.com/Products/ft/sensors.aspx) resembling a metal disk with 40mm diameter, 14mm height and 57g weight. Force was measured in Millinewton (mN) at 1000 Hertz (Hz). Presentation sequences lasted under 4min to prevent motor fatigue and decreasing force amplitudes over trials (Nazir et al., 2017).

Before data collection, we familiarized participants with the sensor and trained them to hold it with a grip force between 1500 and 3000mN by providing visual feedback (cf.

Miklashevsky et al., 2021) until participants could hold the sensor for 5s inside the required range. Calibrations were repeated after each break and before each experimental block.

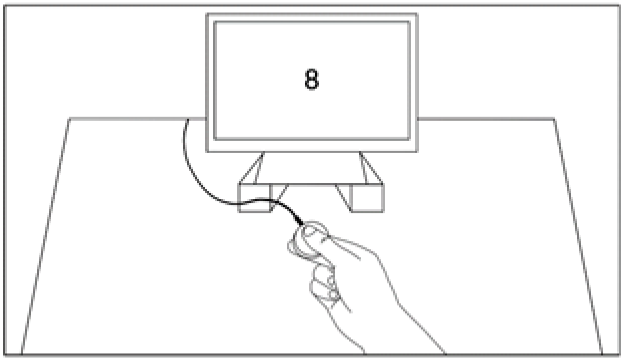

Fig. 2. Schematic representation of experimental set-up showing a hand holding the grip force sensor centrally aligned with the stimulus along the horizontal axis.

2.4 Procedure and Design

We coded numerical magnitude as a categorical variable. To emphasize the categorical contrast between small and large numbers, extreme numbers were presented twice as much as the other numbers. Numbers 1, 2, 8, and 9 were presented 40 times, and the numbers 3 to 7 only 20 times each. Each number was followed by a red number (catch trial) in 20% of trials, deviating from it by either 1 or 2 in 50% of catch trials.

A total of 312 (52 catch trials) trials were presented in random order. The experiment was divided into 4 blocks with a self-paced break (minimum duration of 40 sec) after each block. In addition, 14 random numbers were presented in an initial practice block to ensure the understanding of the task.

Afterwards, participants completed the Edinburgh Handedness Inventory - Short Form (Veale, 2014), the manipulation check, and were debriefed. The total duration of the experiment was approximately 30 minutes.

3. Data Analysis and Results

Data processing and analyses were performed in *Julia* programming language (Bezanson et al., 2017, https://julialang.org/). Reproducible analyses were created with the open scientific publishing system Quarto (https://quarto.org). Analysis scripts are available via the OSF repository (https://osf.io/wx62h/).

A Type I error rate of alpha= .05 was used in all statistical tests reported in this article.

3.1 Data preprocessing

Following Nazir et al., 2017, force data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 15Hz. Stimulus-locked epochs of interest were extracted for each presented number in non-catch trials. Epochs ranged from 200ms before to 2,000ms after stimulus onset. Between trials, force fluctuations were corrected by standardizing at stimulus onset: We subtracted the average force at the 20ms intervals before onset from each epoch. These pre-processed data thus reflect an increase or decrease of force relative to stimulus onset.

3.2 Epoch rejection

We excluded epochs that comprised movement artefacts and large force variations (cf. Miklashevsky et al., 2021, 2022). The rejection criterion was a profile either exceeding maximum or minimum thresholds of ±300mN or a change in force of more than 200mN within a period of 100ms. As a result, 12.8% of epochs were excluded. Data of two participants were discarded because more than 50% rejected epochs.

3.3 Number comparison task

Errors in the number comparison task occurred in less than 2.5% of catch trials, indicating that participants paid attention to the numbers. There were no differences in performance responding to target numbers that were smaller or larger than the previous number and that deviated by 1 or 2, both $t(39) < 1$.

3.4 Cluster-based permutation tests of grip force fluctuations

Spontaneous grip force fluctuations were analyzed using cluster-based permutation tests (Maris & Oostenveld, 2007). This bootstrapping method solves the multiple comparison problem in time-series data and controls family-wise error rates by identifying clusters of potentially substantial differences. These clusters are then tested afterwards for significance using permutation tests of the few mass-statistics for the identified clusters.

To test for systematic difference in grip force, we calculated first the averaged epoch for each participant and condition of interest (e.g., small vs. large numbers). Second, *t*-values for the contrasts in each sample were calculated and clusters of interest were identified for which at least 30 consecutive samples (i.e., 30ms intervals) exceeded *t*-statistics with an associated $p< 0.2$. Third, the sum of *t*-values in each cluster was calculated as a cluster-based statistic. These mass-statistics were then tested for significance using permutation tests. That is, condition labels were randomly assigned and the resulting mass-statistics were calculated. This was done for 20,000 random permutations. The resulting distributions of the cluster-based mass-statistics were used to test the cluster for significance.

Fig. 3 depicts average force profiles when processing small (<5) and large (>5) numbers. Comparing the two conditions revealed the following clusters of interest in ms: 767-958, 984-1062, 1081-1158, 1465-1657, 1660-1727, and 1750-2000. We joined clusters with gaps smaller than 30 samples and identified two clusters of interest (cluster A of 767-1158ms and cluster B of 1465-2000ms). The permutation test revealed that both were significant clusters where the applied force on the grip sensors was significantly higher for large compared to small numbers: cluster A, 767-1062ms, $p= .044$, cluster B, 1465-2000ms, $p= .026$ (see Fig. 3).

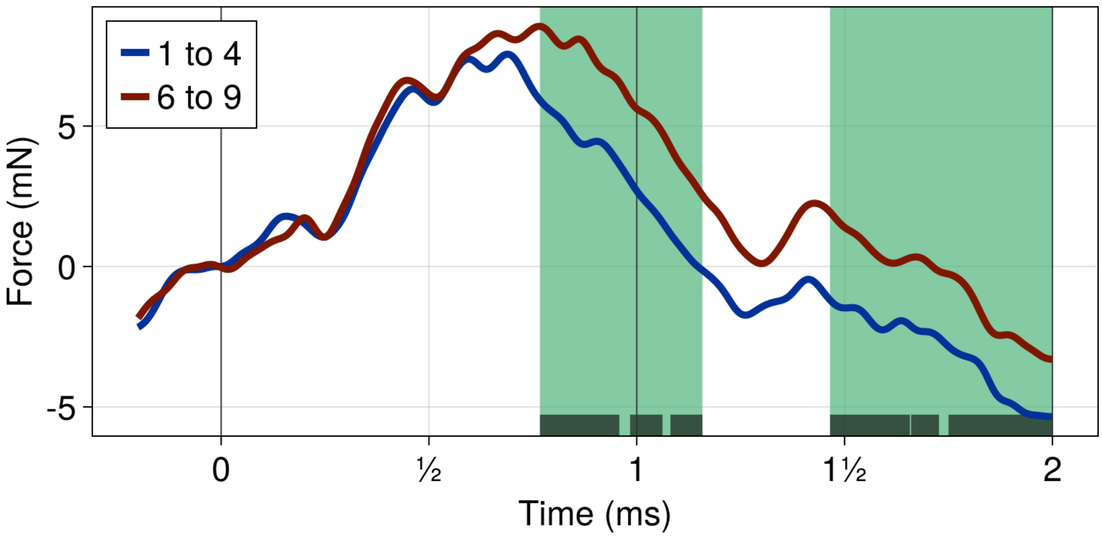

Fig. 3. Average force profile while viewing small and large numbers. Black areas at the bottom indicate the cluster of interest before joining neighboring clusters that are represented by the green area.

Further, we tested whether the effect of number size on grip force was driven by numbers at the lower end (1/2) or upper end (8/9) of the number range or by numbers close to each other (3/4 vs. 6/7) by performing two separate cluster permutations (see Fig. 4).

The cluster permutation test for extreme numbers 1/2 and 8/9 revealed one statistically reliable cluster between 774-907ms, p= .037, while three further tested clusters of interest did not reach significance: 35-72ms, p= .090, 470-519ms, p= .095, 1553-1604ms, p= .120 (see Fig. 4A). For numbers 3/4 and 6/6 that were close to the reference, the sample-wise t-tests revealed 6 clusters of interest: 819-883ms, 1026-1083ms, 1086-1127ms, 1133-1300ms, 1306-1832ms, and 1844-2000ms (see Fig. 4B). After joining neighboring clusters with small gaps, the permutation test revealed in two time intervals that grip force while viewing larger compared to smaller numbers was significantly stronger: 819-883ms, p= .036, and 1026-2000ms, p= .023. Taken together, for numbers close to 5, participants applied more force when processing larger numbers in the interval around 800ms and from about 1000ms till the end of the trial. For extreme numbers, however, this effect was less pronounced and occurred only briefly around 800ms.

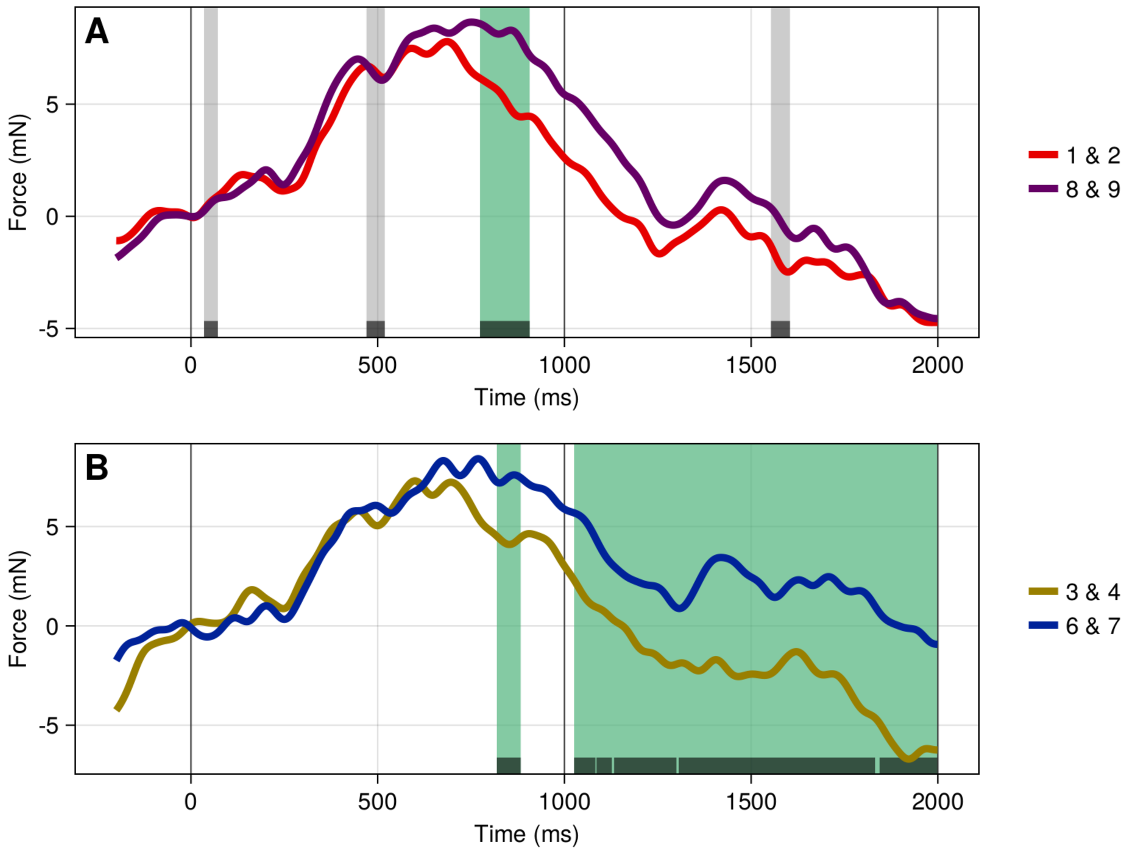

Fig. 4. Average force profile while viewing numbers 1&2 compared to 8&9 (Fig. 4A) and 3&4 compared to 6&7 (Fig. 4B). Black areas indicate the cluster of interest before joining neighboring clusters that are represented by the green area. Identified clusters of interest that are not significant are depicted in grey.

4. Discussion

The current study examined spontaneous grip force fluctuations during number processing. Grip force profiles revealed that the processing of large numbers induces larger grip forces compared to the processing of small numbers. By modelling spontaneous grip force fluctuations with cluster-based permutation tests we tracked the effects of semantic processing on motor activity over time. This means that we quantified force production during semantic numerical processing continuously and relatively to the beginning of the trial. We observed the first significant magnitude-driven dissociation of force profiles between 767 and 1062ms after the number presentation. After this cluster, the average grip force remained higher for large than small numbers. However, this effect was not significant over the entire remaining trial. Intriguingly, the largest cluster and thus the strongest evidence for a systematic dissociation of force profiles was observed at 1465ms after stimulus onset. These late dissociations likely showed semantic processing for our 1-back task. It required holding an item in working memory in anticipation of a possible catch trial.

The current finding extends previous research on the coupling of numbers and motor force since it demonstrates for the first time the quantification of motor force induced by symbolic numbers. The quantification of motor force is a critical extension to previously reported similar but dichotomous effects. It challenges non-embodied and stimulus-response based theories such as the polarity-correspondence account (Proctor & Cho, 2006; Proctor & Xiong, 2015). For instance, full vs. precision grasp actions (Andres et al., 2004; Lindemann et al., 2007) and strong vs. weak button response types (Krause et al., 2014; Vierck & Kiesel, 2010) can become associated with compatible codes to large and small numbers, respectively. According to the polarity-correspondence account, faster executions of compatible motor responses are then driven by structural similarities of the concepts “small number” and “large number” with “weak force” and “strong force”.

Such dichotomous associations are based on their qualitative similarities and rely on metathetic variations. Therefore, they should not be interpreted in favor of a common within-magnitude mechanism such as the generalized magnitude system (Casasanto & Pitt, 2019) that is proposed by ATOM (Walsh, 2003, 2015). In contrast, The Number-Force Magnitude Associations (NuFoMA) effect found in this study describes how number magnitudes directly and continuously affect the prothetic dimension of force. Therefore, NuFoMA provides direct support for the idea of a common generalized magnitude system that is shared by numbers and actions as proposed by ATOM (Walsh, 2003, 2015) and other embodied models of number processing such as the sensorimotor grounding perspective (Sixtus et al., 2023) that emphasize the continuous shaping of conceptual knowledge by sensorimotor activities (see also Abrahamse & van Dijck, 2023, for a situated account).

The current study is among the first to quantify motor force during a size task. Previously, an effect of motor force was demonstrated in 2.5- 3-year-old toddlers playing a computer game in which they moved a cargo with different numbers of objects to the top of a screen by pressing a knob (Krause et al., 2019). Although the pressing had no effect on the control dynamics of the game, children applied more force when more objects had to be lifted. Importantly, the presented numerical information was non-symbolic and corresponded 1-to-1 with the physical size and associated weight. The authors discussed the observed force modulation without reference to theories on number representation and interpreted it as evidence for perceptual-motor coupling of magnitudes in early childhood.

The present study demonstrates similar coupling in another domain and with adults. Such a generalization supports the idea that semantic representation is grounded in sensorimotor experiences (Barsalou, 2008; Fischer, 2012; Matheson & Barsalou, 2018; Muraki et al., 2023).

3.1 Limitations

To measure NuFoMA, we utilized a grip force sensor that all participants held with a precision grip. However, precision grip actions might have led to an underestimation of NuFoMA. As a study on numbers and grasping demonstrated, precision grips (Lindemann et al., 2007) and hand closures (Andres et al., 2004) are associated with smaller magnitudes while power grips and hand openings are associated with larger magnitudes. In our study, this could have produced two conflicting associations. On the one hand, we have the hypothesized positive correlation between number magnitude and applied force as proposed by ATOM (Walsh, 2003, 2015). On the other hand, the congruence between small numbers and hand-closing actions (Andres et al, 2004) might have resulted in the negative number-force correlations, that is, an increased applied force towards smaller numbers. If this was the case, then we underestimated NuFoMA leading to larger applied forces during smaller numbers and smaller applied forces during larger numbers. However, it is questionable if such contrasting associations emerged in our study due to the design of the task that recorded spontaneous fluctuations excluding intentional responses. Therefore, no active actions were needed that could have produced the conflicting associations reported by Andres et al. (2004).

The effect could have been further underestimated considering the structure of the catch trials. The catch trials were designed to always differ by “one” or “two” from the previous number. We have opted for the design to make the task as easy as possible while ensuring participants’ attention to the task and the semantic processing of number magnitudes. Our task included a total of 52 (16.7%) “one” or “two” responses. Even though the responses during the catch trials were excluded from the analysis, the response pattern might have led to a bias subjectively making smaller numbers appear more frequent than larger numbers. This is relevant to consider because frequency is known to correlate with motor magnitudes. For instance, responses to more frequent words produce larger motor magnitudes than to less frequent words (Balota & Abrams, 1995). For numerical cognition, smaller numbers are more frequent than larger numbers (Coupland, 2011). If the effect of frequency on motor magnitudes also translates to numerical cognition, then smaller numbers should have produced larger forces than larger numbers and, therefore, constituted an alternative model depicting a negative correlation between numerical magnitudes and motor magnitudes. This was not the case. However, it is possible that our task design produced some global effect where smaller numbers (especially one and two) produced slightly more force.

3.2 Conclusion

The current study reports NuFoMA (Number-Force Magnitude Associations) as a within-magnitude effect describing how semantic numerical magnitudes affect motor magnitudes. Larger numbers induce larger grip forces than smaller numbers. We report NuFoMA under conditions that do not require intentional responses and rather rely on continuous grip force recordings. The fluctuations of the grip force are spontaneous and mirror semantic numerical processing.

CRediT authorship contribution statement

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Acknowledgments

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