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Theoretical Contributions

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A Theoretical Position Statement on Mechanism Underlying Numerical Cognition

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Abstract

This theoretical statement addresses the lack of a homogenous understanding of what constitutes a "mechanism" in studies in numerical cognition. Despite the increasing focus on mechanisms in the field, ambiguity exists in how mechanisms are defined and interpreted. To address this, I propose a conceptual framework that outlines three levels of mechanisms: micro-, relational, and macro-level, that each correspond to different levels of mechanisms to understand associations in the research field of numerical cognition. The micro-level mechanisms refer to a process-oriented perspective. The relational level refers to a perspective with a focus on underlying associations between variables, and finally the macro-level mechanisms refer to theory-oriented perspectives. I hope that this framework will serve as a starting point for future dialogue, providing clarity and promoting consistency in the conceptualisation of mechanisms in the field.

Keywords

numerical cognition, mechanisms

Recently, there has been an increasing interest in discovering mechanisms underlying relations between early cognitive skills and mathematics achievement (Gilmore, 2023), which was also voiced at the Mathematical Cognition and Learning Society conference in 2023. Previous research has extensively investigated what cognitive skills can be identified as significant contributors to mathematics at different ages, both cross-sectionally

(Calderón-Tena, 2016; Coolen et al., 2023; Cragg & Gilmore, 2014) and longitudinally (Bull et al., 2008; LeFevre et al., 2010; Mazzocco & Kover, 2007; Passolunghi et al., 2008), see Agostini et al. (2022) for a recent review of cognitive skills related to mathematics difficulties and dyscalculia. However, many 'hows' and 'whys' remain either elusive or are not empirically tested. This limits our insight into understanding the underlying mechanisms.

I have come to believe that the current literature forms an obstruction to understanding mechanisms. While the aim of many researchers is to discover underlying mechanisms, the level to which these are mechanisms is not entirely clear.

Indeed, while I have on several occasions presented on potential mechanisms underlying cognitive skills and mathematics, these presentations have often been met with the question of what I believed the involved mechanisms were. Thus, there seemed to be a misalignment between my understanding of mechanisms and the understanding of mechanisms that my fellow researchers had. On other occasions, I came across work claiming to explore underlying mechanisms of mathematics, where I was not convinced that underlying mechanisms were identified or even investigated. This seemed to highlight a disparity in how 'understanding underlying mechanisms' are conceptualised or interpreted within the field of numerical cognition.

As research in numerical cognition increasingly shifts its focus to understanding mechanisms underlying the previously identified relations between early cognitive skills and mathematics, it is important to become aware of the lack of a homogenous understanding and to clarify the conceptual foundations of 'underlying mechanisms'.

Current and Past Views on Mechanisms in Cognitive Science

The inconsistency in how the term mechanisms is used both in the broader cognitive science and other disciplines such as neuroscience and biology is not novel and this issue has previously been recognised and has received attention in various ways (Bechtel & Abrahamsen, 2005; Craver, 2013; van Bree, 2024). An early and widely referred to framework in cognitive science is Marr's three levels of analysis approach (Marr, 1982). Marr (1982) suggested that to fully understand a cognitive system (i.e., any information-processing system) researchers need to answer questions at three different levels: the computational level, the algorithmic level and the implementation level.

The computational level refers to the abstract computational theory of a system. Questions that need to be addressed to understand this level according to Marr are: *"What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?"* (p. 25, Marr, 1982)

The algorithmic level refers to the representations of the input and output and which algorithm is used to transform input into output. This level can be understood through the questions: "*How can this computational theory be implemented? What is the representation for the input and output, and what is the algorithm for the transformation?"* (p. 25, Marr, 1982).

The implementation level refers to the details of the physical realisation of the representations and the algorithm, leading to the question: *"how can the representation and algorithm be realised physically?"* (p. 25, Marr, 1982).

Although Marr's framework was originally one developed to understand computational information-processing systems rather than broader underlying mechanisms of cognitive functioning, Zednik (2017) argues that variations of the questions asked on each of Marr's proposed levels are appropriate when aiming to discover and describe cognitive mechanisms. Indeed, the author proposed that questions on the computational level could represent questions on *what* a cognitive system does and *why*. The second algorithmic level could describe the behaviour of a cognitive system, in particular *how* the cognitive system functions. Finally, the implementation level could represent questions on *where* a particular operation (i.e., as a component of a mechanism) is carried out.

Van Bree (2024) proposed an additional step to the three levels of analysis approach by Marr applicable to cognitive neuroscience research. The author states that cognitive neuroscience research goes through a pre-mechanism stage and a mechanism stage. While the mechanism stage could reflect Marr's three levels of analysis approach, the pre-mechanism stage reflects the process of "narrowing down where and when mechanisms are situated in space and time" (van Bree, 2024). While this stage is not part of the mechanistic explanation, it provides the basis for investigating the mechanism.

However, Marr's framework has received criticism on various fronts, in particular concerning the lack of clarity on how to address these questions to understand systems and how to find empirical support (van Bree, 2024; Zednik, 2017). Furthermore, while this framework can be used to provide meaningful insight into information-processing systems such as cognitive systems, it does not specify what constitutes an underlying mechanism in cognitive science. Moreover, it fails to take into account the broader context of cognitive systems. For example, mechanisms are part of a larger environmental organisation (including bodily, social and other environmental factors) and are able to alter their behaviour depending on conditions in the environment (Bechtel, 2007). Therefore, the phenomena that researchers are trying to understand are shaped by and shaping larger environments or contexts.

Bechtel (2023) addressed these limitations in neuroscience by highlighting that the brain uses many information-processing structures simultaneously, which are integrated in a network. While Marr's levels focus on different perspectives to understand the same information-processing system, Bechtel proposed that to understand a mechanism fully, we need to decompose systems into parts, operations, and the organisation. Parts are the structural components of a system, the operations are the processes of a system and the organisation explains how the parts and operations of a system connect (Bechtel,

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2007). Within a living system, these organisations are complex. Rather than focusing on one information-processing system, we should recognise that there are many systems and learn how they connect together. Indeed, systems carry out their activities, but also influence each other (Bechtel, 2023).

Applying Mechanistic Frameworks to Numerical Cognition

Bechtel highlights the need to decompose complex systems into simpler sub-processes and their interrelations to understand the mechanism of a phenomenon. Numerical cognition research reflects this by decomposing complex numerical abilities into specific cognitive processes (i.e., including parts and operations) and examining how they interact. For example, when studying the representations of numbers, studies have identified two key parts among others, the Approximate Number System (Dehaene, 1997; Halberda et al., 2008), and the Object Tracking System (Feigenson et al., 2004). These parts are systems that represent numbers, but in different ways. The Approximate Number System operates by approximately estimating large quantities, and the Object Tracking System individually indexes each item in a small set (Feigenson et al., 2004). These are decomposed processes to understand mechanisms of how humans represent numbers, however, both processes are needed when studying the mechanisms of how humans process numbers of all magnitudes in symbolic number learning.

However, a limitation of this view is how researchers practically study the organisation and interaction between systems to clarify mechanistic understanding rather than identifying associations (i.e., is there an association?) between systems, which cannot necessarily identify mechanisms (i.e., how do they associate?). This issue is particularly present in current research in numerical cognition, however, it does not mean that studies identifying associations lack value in the bigger picture of studying mechanisms. Indeed, what these studies can do relates to the pre-mechanisms stage that aims at narrowing down where and when mechanisms are situated (van Bree, 2024). In other words, under what conditions these mechanisms function or fail to function. This further relates to the dynamic interplay highlighted by Bechtel (2023), which can be particularly important in numerical cognition. Indeed, multiple cognitive systems, such as attention, memory, quantity representations, influence each other and must work together to support number learning. Thus, how cognitive systems function and interact can support or limit one another, creating different conditions under which a mechanism might or might not function.

A particular challenge to study underlying mechanisms in numerical cognition using the existing frameworks (e.g., Marr, 1982; Bechtel, 2007), reflects the relatively recent invention of mathematics. Therefore, mathematics relies on neural and cognitive functions originally meant for other purposes, that have been adapted for specific mathematical purposes (Dehaene & Cohen, 2007), unlike more evolutionary cognitive systems. These evolutionary systems, such as processing visual information, are the systems often used as examples to illustrate how mechanistic frameworks identify underlying mechanisms (Bechtel, 2007; Marr, 1982). Within numerical cognition research, what a cognitive system does and why, might have to become what a cognitive system can do and why does it do what it was not originally intended to do. This added complexity makes it difficult to translate empirical work on mechanisms underlying numerical cognition to existing mechanistic frameworks. The three levels of analysis approach by Marr (1982) studies one specific information-processing system separately from others. While Bechtel (2023) emphasises that multiple systems interact dynamically, it does not provide guidance on how these dynamic interactions can be empirically tested or brought together to provide a broader picture for fully understanding a mechanism.

I will propose different levels at which current research in numerical cognition often refers to mechanisms, highlighting how they fit together. After outlining the aim and introducing the different levels, I will compare how my framework both overlaps and complements the introduced existing perspectives.

Aim

My aim for this statement is firstly to stimulate a discussion on the topic of conceptualising 'mechanisms' in numerical cognition and to raise awareness of the different ways these mechanisms can be understood. As a way to clarify the current uses in the literature of 'underlying mechanisms', a conceptual framework including three different levels of mechanisms will be suggested. Each level corresponds to different aspects of the relations between cognitive skills and mathematics achievement. This framework is likely not a definitive, exhaustive solution but acts as a way to clarify the current understanding of the topic and to provide an opening for future dialogue.

Levels of Mechanisms

Rather than claiming that one kind of finding does not target mechanisms and another does, I believe that research can advance our knowledge about mechanisms on different levels. In this framework, I propose three distinct (although not necessarily mutually exclusive) levels of mechanisms: *micro-level, relational level, and macro-level.* Each of these levels corresponds to a different conceptualisation of what constitutes a "mechanism" in numerical cognition. They represent different ways of thinking about mechanisms, which can be used in combination to provide a more holistic understanding of how cognitive skills underly mathematical learning.

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Level 1: Micro-Level

At a micro-level, mechanisms refer to a *process-oriented perspective* of associations between cognitive skills and mathematics. Research on mechanisms at a micro-level has a step-by-step nature of specific cognitive processes that underlie certain associations. Studies at this level aim to address the question of "*how* two specific skills are associated" or "what process underlies it".

To address the mechanisms on a micro-level, researchers need clear process-oriented hypothesis, accompanied by fine-grained measures or experiments to isolate specific cognitive processes and their effects on mathematical tasks.

Example of Micro-Level Mechanism

An example of a study exploring mechanisms on a micro-level, investigated the specific inhibitory control processes at play when performing numerosity judgement tasks (Viarouge et al., 2019, 2023). While previous literature had highlighted that numerosity judgement tasks were associated with inhibition (Fuhs & McNeil, 2013), Viarouge et al. (2019) delved deeper into the mechanisms of this association, by testing and providing support that the underlying process corresponds to the inhibition of the irrelevant non-numerical dimensions of magnitudes within a numerosity judgement task. Moreover, Viarouge et al. (2023) went another step further demonstrating that the inhibitory control processes underlying the inhibition and numerical judgement association are specific to the conflicting dimensions of magnitude.

While these mechanisms might not be the sole mechanisms underlying the association between inhibitory control and numerosity judgement tasks, they describe clear processes on a micro-level. With this study, the authors tested clear process-oriented hypothesis, with fine-grained measures in an experimental design. This enabled the authors to find detailed insights into the micro-level mechanisms.

Level 2: Relational Level

At a relational level, mechanisms refer to a perspective with a focus on associations between a variety of variables in order to explain in more detail previously found relations between two variables. This does not explain potential underlying processes, but it strives to understand interactions, mediating factors, or whether associations hold when considering growth trajectories, mutual development, or other dynamic relations between variables. Studies investigating mechanisms on this level often address *under what conditions* (e.g., when, for whom, in what context) relations hold or change.

While these studies are still on a relational level and thus fall short of providing a deeper understanding of underlying mechanisms, they are designed to provide valuable insights into the structure and dynamics of relations, offering a foundation for understanding potential mechanisms and informing future, more process-oriented research.

Example of Relational Level Mechanism

An example of a study exploring mechanisms on a relational level, is by Price and Wilkey (2017), aiming to test mechanisms underlying the relation between non-symbolic magnitude processing and symbolic number processing. To do so, the authors tested two hypotheses, the 'mapping' hypothesis suggesting that symbolic numbers are associated with their non-symbolic magnitude representations, compared to the hypothesis that the association between non-symbolic and symbolic processing is accounted by shared cognitive resources (i.e., executive functions). Non-symbolic to symbolic mapping and executive functions were used as mediators in mediation analyses, highlighting that both mediators were important underlying factors to the association between non-symbolic and symbolic processing.

This study does not directly test underlying processes between associations, but it does allow to test underlying factors to an association on a relational level, bringing further insight in potential mechanisms.

Level 3: Macro-Level

At the macro-level, mechanisms refer to broader, *theory-oriented* explanations of why certain cognitive skills are related to mathematics. This level of mechanisms aims to explain the *why* of associations between general constructs by integrating them into larger frameworks. Examples of these general constructs are academic achievement and cognitive abilities, such as Peng and Kievit (2020) describing several macro-level potential mechanisms underlying the bidirectional relations between academic achievement and cognitive abilities (i.e., Cattell's investment theory, semantic bootstrapping, transactional processes, or learning experiences).

At this level, researchers hypothesise about theory-oriented explanations for associations or overlap between constructs. These macro-level mechanisms are mostly theoretical in nature and mechanisms on another level are often required to find support with empirical data.

Example of Macro-Level Mechanism

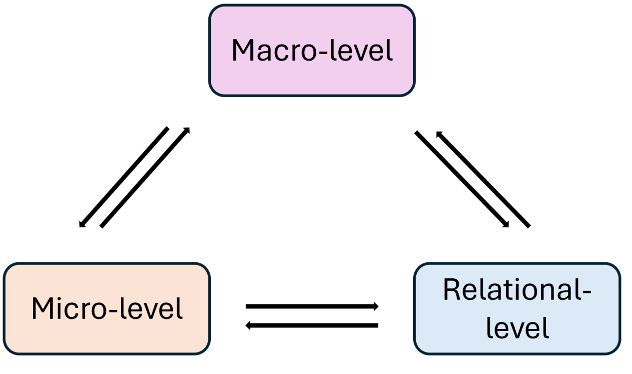
An example of a macro-level mechanism in numerical cognition was originally suggested by Dehaene (2005) who proposed the term "neuronal recycling" as neuronal mechanism by which we solve mathematical problems. As mathematics is a too recent cultural invention to have a dedicated neural circuit, Dehaene suggested that to perform mathematical tasks, humans reuse evolutionary circuits originally serving a different goal. Based on this theory, Hubbard et al. (2005) further suggested a macro-level mechanism that neuronal mechanisms supporting spatial attention, would also support arithmetic abilities (shifting attention on a mental number line). A mechanisms for which Knops et al. (2009) later found support on a micro-level, showing that the neuronal activation pattern during additions and subtractions resembled the activation pattern of respectively rightward and leftward eye movements.

An Integrative View

While presented as distinct, the three levels of mechanisms should be understood as interconnected perspectives, see Figure 1, rather than as isolated categories. The distinction lies in the scope and focus of the research question, not in fundamentally different kinds of mechanisms. Empirical support at one level can *indirectly* support mechanisms at another level. Indeed, findings on a relational level could indirectly constrain the possible micro-level processes or challenge macro-level theories (e.g., by revealing inconsistencies in findings under certain conditions). Similarly, studies on micro-level processes and macro-level theories can indirectly support each other or uncover new perspectives (e.g., by demonstrating consistency or identifying mismatches between empirical support and theory). A comprehensive understanding of underlying mechanisms is likely to require contributions and thorough insights at each level. One potential challenge in the current literature on mechanisms in numerical cognition is that research can remain focused within specific levels, building on previous studies at the same level rather than building on insights across levels. Highlighting gaps in how insights flow between levels, and designing studies that bridge them, can help move the field towards a more comprehensive understanding of mechanisms.

Figure 1

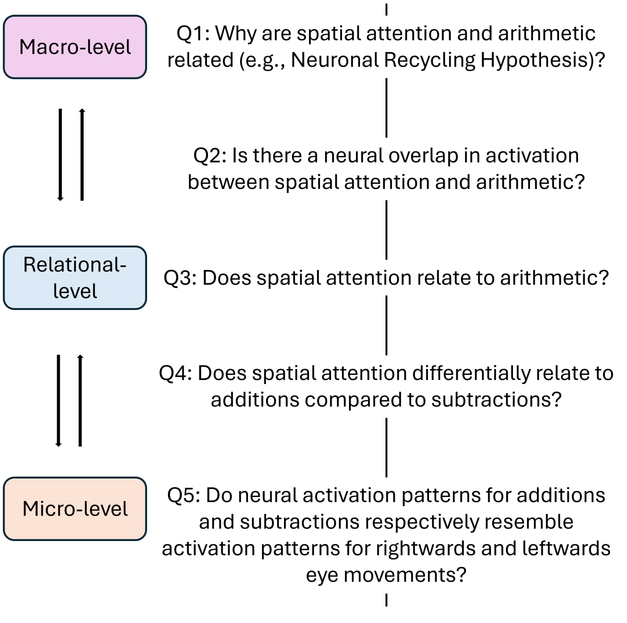
Interconnected Representations of the Three Levels of Mechanisms



Moreover, narrowing or broadening the scope of research topics and questions can represent a shift in the level of mechanism under study. Figure 2 shows an example of how a specific research topic can be narrowed or broadened to move along a continuum between two levels. This highlights that these levels are not strict boundaries but points along a continuum. To use Figure 2 as an example, moving from Q3 (“Does spatial attention relate to arithmetic?”) to Q4 (“Does spatial attention differentially relate to additions and subtractions?”) narrows the scope of the research question but remains within the relational level. Q4 is simply positioned several steps closer to the micro-level. Similarly, Q2 (“Is there a neural overlap in activation between spatial attention and arithmetic?”) examines associations and remains on the relational level, but it sits closer to the macro-level as it produces results that can be used more directly to support or challenge the theoretical mechanism. This continuum structure allows researchers to position the aims of their research questions (e.g., process-oriented vs theory-oriented), while still recognising the underlying level being addressed.

Figure 2

Examples of Research Questions Along the Continuum Between Levels



Note. This illustration is an example of where research questions can be positioned in relation to the different levels of mechanisms. These questions are purely illustrative and are not intended to suggest that the underlying mechanisms of this particular topic are fully understood through these questions.

Comparing Past and Current Mechanistic Frameworks

The current framework has several points of overlap with previous mechanistic frameworks, displayed in Table 1, as well as some complementary points.

Table 1

Comparison Between Different Mechanism Frameworks

Current three-level framework	Marr's three levels of analysis approach	Bechtel's mental mechanism perspective	Van Bree's perspective on neural mechanisms
Micro-level	Algorithmic level	Parts and operations	Mechanism stage
Relational level	–	Organisation	Pre-mechanism stage
Macro-level	Computational level	–	–

Micro-level mechanisms reflect the algorithmic level in Marr's three levels of analysis approach, as they represent which algorithm transforms input into output in one given information-processing system. Although research on a micro-level often focuses on one specific process, it is in theory not limited to one specific system, but in both frameworks, the aim is to identify fine-grained detailed processes. Therefore, micro-level mechanisms also map onto the parts and operations components by Bechtel (2007). While Bechtel separates parts and operations, research that is process-oriented in the current framework, will mostly integrate both components to understand underlying processes. Finally, when considering van Bree's split in a pre-mechanism stage and a mechanism stage, the micro-level research most closely aligns with the mechanism stage which reflects algorithms and the parts of the brain performing them.

Relational level mechanisms are not considered in Marr's approach, which only focuses on a single system at a time. However, it resembles Bechtel's organisations, connecting and integrating different systems. The relational level goes a step further, highlighting under what conditions relations and processes change. This way, the relational level can inform when and where mechanisms are situated, in line with the pre-mechanism stage by van Bree (2024). In accordance with the pre-mechanism stage, relational level research does not necessarily test underlying mechanisms directly, however, it can provide insight on the dynamics of how systems associate in line with Bechtel's integrative network of systems (Bechtel, 2023).

Finally, macro-level mechanisms, although not clearly represented in van Bree's and Bechtel's perspectives, they can partly map on the computational level in Marr's framework. Indeed, the computational level reflects what a system does and why, which can be on a theoretical level. While the macro-level can consist of a theoretical perspective of a single system, it allows researchers to form theoretical mechanisms across multiple systems and interrelations.

Although there is overlap between the frameworks, this three-level distinction does not aim to replace these existing frameworks, but aims to make sense of current research in cognitive science and in particular in numerical cognition. Indeed, current research often aims to identify mechanisms, but does so at different levels and with different assumptions. The three levels described here might help structure existing and future research, clarifying the different kinds of insight necessary for a full understanding of mechanisms. As such, the current framework makes for a more practical guide on where to position empirical work in numerical cognition and highlight gaps in the larger mechanistic understanding, as information on each level is likely required.

Conclusion

The current use of 'mechanisms' in the numerical cognition literature does not consistently refer to the same meaning or as I suggest, level. Therefore, the field as a whole could benefit from a clarification and more alignment on the meaning of underlying mechanisms, regardless of whether the terms used in this statement are used or whether another clarification is given. With this framework consisting of three levels of mechanisms, I propose that rather than assuming that one level is not a mechanism, while another is, it might be worth clarifying at the start of a study design and/or at the start of a manuscript which level of mechanisms the authors aim to investigate.

Whether all three levels are *true* underlying mechanisms remains open for discussion and I hope this statement will encourage colleagues to discuss this further. For the moment, I believe that making a distinction on what level of mechanisms you are hoping to tackle might avoid confusion in future literature. I further also believe that with this multi-level framework, each level captures a unique aspect of understanding the mechanisms. They can be interconnected and complementary in nature (e.g., empirical support on micro-level can confirm macro-level mechanisms, while relational level mechanisms could inform theories of mechanisms on a macro-level). For a comprehensive understanding of underlying mechanisms, it is likely that an understanding on all three level is required. It is important to recognise that the framework is a starting point, and future dialogue should continue to refine our understanding of mechanisms in the field of numerical cognition.

Limitations

While I believe the three-level framework provides a useful starting point for understanding mechanisms, there are several limitations to this statement. First, I recognise that in practice the distinction between the three levels could be challenging and differences between the ‘how’ and ‘why’ of mechanisms are difficult to interpret.

Second, some studies investigating mechanisms could span multiple levels creating hybrid mechanisms, thereby not fitting well within this framework; although I would still encourage authors to report what level of mechanisms they are trying to address, regardless of whether it fits well within the current framework.

Third and related to the previous point, it is unlikely that this framework is exhaustive, and other levels or dimensions of mechanisms may exist that do not neatly fit within the current three proposed levels.

Moreover, I want to mention that mechanisms confirmed in the literature on any level are not necessarily true across multiple populations or developmental stages and the full comprehension of mechanisms underlying two variables is likely going to involve multiple mechanisms for each level.

On a final note, what this framework does not address are larger methodological issues in the field. Indeed, studies that aim but fail to identify mechanisms also stem from methodological shortcomings such as not relying on existing theories, choosing variables without specific theory-driven hypotheses, or using unreliable measures. These issues can more frequently be observed on a relational level and are likely not going to be resolved by increasing our conceptual understanding of mechanisms. However, I am hopeful that by emphasising the importance of building bridges between the three levels and to link our understanding across all three levels, studies that truly aim to explore underlying mechanisms (or parts thereof), will build on the knowledge available from other levels when designing studies, instead of only building on previous research within the same level.

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