IS SPEED A MAGNITUDE?

Neurocognitive Estimations of Speed and its’ Connection to Time, Space and Numeric/Quantity Estimations

An Experimental Study

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Abstract

Associations between space, time, numbers and quantities have suggested that there must be a shared representational format which underlies them. One of the more prominent theories of an underlying system of representation is that of ATOM, which suggests that there exists a generalized system of magnitude which processes these dimensions. However, there has been no study that examines whether speed is also processed within such a system. This study investigates this by seeing if a SNARC or Problem-Size effect arise in two speed estimation tests. The fundamental task for the participants in both tests was to judge which of two stimuli was the fastest, with the stimuli moving towards a wall located in the center of a computer screen. Their correct discrimination and response time was recorded. The results found that there were no significant results for either effect. This might be due to low sample size, methodological difficulties, and low robustness. Future research might amend these difficulties by having a more consistent setup with more trials reflecting the effect being tested and fix some potential problems with the test environment.

Keywords: Speed, Time, Number, Space, Mental Line, Magnitude, ATOM, Problem Size, SNARC
Acknowledgements

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# Abbreviations and Terminology

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td><strong>ANS</strong></td>
<td>Stands for Approximate Number Sense. This system within the brain is crucially involved in the approximation of the amount of discrete objects in a set. Evidence suggests that it is both active in number processing specifically, and other magnitudes more generally.</td>
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<td><strong>ATOM</strong></td>
<td>Stands for A Theory Of Magnitude. It posits that there is a dedicated, generalized system within the brain which function is to process all magnitude phenomena.</td>
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<tr>
<td><strong>DD</strong></td>
<td>Stands for Developmental Dyscalculia, which is a type of mathematical learning disability found in children.</td>
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<tr>
<td><strong>Dimension(s)</strong></td>
<td>Refers to Space, time, and numbers in ATOM. Whether speed can be included as another, distinct dimension is yet to be discovered.</td>
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<tr>
<td><strong>IPS/IPL/IPC</strong></td>
<td>Stands for Intraparietal Sulcus, Intraparietal Lobule, or Inferior Parietal Cortex are specific areas in the parietal lobe of the brain. These regions are especially relevant in integrating the magnitude dimensions.</td>
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<tr>
<td><strong>Magnitude</strong></td>
<td>Refers primarily to the property of size that is present in time, number, space, speed and other quantities. Evidence suggests that magnitude is not merely metaphorical in its’ relation to these dimensions. More concretely, it has been posited that magnitude is the underlying neuropsychological representation for these quantifiable phenomena.</td>
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<tr>
<td><strong>M(T)L/M(N)L</strong></td>
<td>Stands for Mental (Time/Number) Line or Mental (Time) Line hypothesis. The hypothesis is that time and number is represented spatially along a line where small sizes of time and number can be placed at one end and bigger sizes at the other end.</td>
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<tr>
<td><strong>Number</strong></td>
<td>Refers to the symbolic object of numerosity or quantity, i.e. ‘1’, ‘5’, ‘9’ etc. These discrete objects are represented in the brain possibly by the ANS.</td>
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<tr>
<td><strong>Numerosity</strong></td>
<td>The countable property of an object.</td>
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<tr>
<td><strong>Problem-Size (PZ)</strong></td>
<td>The Problem-Size effect is that two numbers which are large in numerical magnitude are harder to discriminate than two numbers of smaller numerical magnitude.</td>
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<tr>
<td><strong>Quantity</strong></td>
<td>The numeric property of an object.</td>
</tr>
<tr>
<td><strong>Space</strong></td>
<td>The neuropsychological aspects of space is the relevant consideration in this paper handles the word ‘space’. How the processing of spatial features in the environment is grounded in the brain.</td>
</tr>
<tr>
<td><strong>SQUARC</strong></td>
<td>Stands for Spatial Quantity Association of Response Codes. See SNARC.</td>
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<tr>
<td><strong>STEARC</strong></td>
<td>Stands for Spatial-Temporal Association of Response Codes. This effect provided behavioral evidence for the existence of the ML for both temporal and spatial phenomena. See SNARC.</td>
</tr>
<tr>
<td><strong>STEM</strong></td>
<td>Stands for Science, Technology, Engineering, and Math.</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>The neuropsychological aspects of time is the relevant consideration in this paper, i.e. how the processing of temporal features in the environment is grounded in the brain.</td>
</tr>
<tr>
<td><strong>Weber’s Law</strong></td>
<td>Weber's law states that the change a stimulus undergo that just noticeable will be a constant ratio of the stimulus original intensity.</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>Speed in this paper refers to the actual displacement of an object in time, relative to some point of observation. How speed is represented by the brain, to facilitate accurate speed estimation, is the primary question in this paper.</td>
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<tr>
<td><strong>Velocity</strong></td>
<td>This term is interchangeable with speed, although usage might differ slightly.</td>
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Summary

Within the neuropsychological literature, many associations have been found between time, space, and numbers at multiple levels of analysis. Such associations have been found in terms of brain regions which processes these dimensions, in psychological experiments which demonstrate their interdependence, and their connections to mathematical ability. Several theories try to give theoretical foundations as to why these associations are abundant, either in terms of their shared representational format, as they can be placed on a mental line, or theories of their functional and systematic interrelatedness.

Purpose

The purpose of this study is to investigate whether speed connects to time, space, number, and other quantities by way of being similarly processed. If speed display similar processing characteristics to that of other quantities, this might give further support the theory of there being a dedicated, generalized system of magnitude which processes all of these neuropsychological phenomena.

Research Questions

1. Is there evidence of a SNARC effect in speed estimation?
2. Is there evidence of a Problem-Size effect in speed estimation?
Introduction

Space, time, numbers, and speed are what can be called ‘magnitudes’ in the linguistic sense. They are understood as continuous features of the world that the mind has extracted out. But to posit a theory of their common, underlying representation in the mind however, is to go a step further. It is to imply their commonalities and connections are not merely linguistic. It is to claim that the processing of one of these extracted dimensions, such as space, is not fundamentally different from another, such as time and numbers.

A first step in finding a representation is to establish the interrelation of these dimensions in terms of shared processing. Evidence of shared processing has been discovered, in the form of many associations, along with transfer effects, within the psychological literature.

Space and Time Associations

Investigations into the psychological association between space and time have proceeded since the 19th century (Mach, 1897). Renowned psychologist Piaget studied how children conceived of time and space (Piaget, 1927/1969). He demonstrated that time and space formed an inseparable whole in the child's mind. The relationship was still asymmetrical, in that spatial aspects could be absent of temporal aspects, but not the other way around. That is, Children used spatial information inadvertently when considering time (Piaget, 1946/1970). Boroditsky's experiments (2000) point to evidence that time’s more abstract nature is concretized by space. Space and distance is more grounded in changing experience, and time is then in turn mapped out through that spatial information. Time is also spoken of in spatial terms in several languages, such as a ‘long’ or ‘short’ vacation (Casasanto & Boroditsky, 2008). Findings by Casasanto and Boroditsky suggest that such spoken associations do not arise out of convention. Time does seem to be spatially represented before verbalization. Other findings show that even manipulating spatial attention via invasive techniques affect time estimations (Vicario, Caltagirone, & Oliveri, 2007).

Associations to Quantity

What also seems to be clear is there is an association between quantity, space and time. Quantities are defined here as non-symbolic entities which have the potential of being quantified. Pitch, duration, loudness, brightness are examples of such quantifiable stimuli. There are several modern studies which associate such quantities with space and time. Levin
conducted experiments (1977, 1979, 1982) where children were to judge which of two lights shone for the longest time. The lights differed in brightness and in size and the children judged the larger or brighter stimuli to have shone for more time. Such associations between time and quantity are also found in non-human animals. When rats are to judge the number of tones in a sequence or the tones’ duration, they treat the differing phenomena the same (Church & Meck, 1984). Tones of 4 and durations of 4 seconds are generally discriminated as being double of 2 and half of 8 by the rats. Such discriminatory powers suggest a more precise association of time and quantity. When quantity can be separated into discrete entities, one might also have to look at an association of these phenomena with numbers specifically.

**Associations to Numbers**

A corollary to quantity is the symbolic representation of quantity, namely, numbers. For numbers is simply the symbolic representation of quantity. Both infants and in non-human animals have abstract representations of numbers (Dehaene, Dehaene-Lambertz, & Cohen., 1998). This rudimentary numerical cognition gives some animals the ability to represent objects in terms of their amount. In humans, this ability extends to magnitude or size estimations (Stevens, 1951). Even subjective intensity can be represented in terms of numbers. This is seen in Stevens work. Stevens performed several studies on the psychological nature of mathematics. Here found that objects relevant to mathematics like distance and duration could be easily estimated and represented as numbers by the participants. Such estimations also followed Weber’s law. Weber’s law more precisely deals with the constant ratio a stimulus undergoes. A change a stimulus undergo that is just noticeable will be a constant ratio of the stimulus original intensity (Fechner, 1860). Stevens experiments showed behavioral associations between numbers and amount with space and time (1951). They were associated even in the sense that their constant ratios were equal. Other experiments in psychophysics also point to the translatability between dimensions in terms of their behavioral similarity in accordance with Weber’s law. These experiments show how brightness can be measured in terms of handgrip pressure, line length, number, and loudness (Stevens & Marks, 1965). Quantifiable stimuli could thus be matched in intensity despite being of different modality.

Lower-order, behavioral associations are thus abundant. There is further evidence which of a higher order association in the are of higher order, cognitive functioning.
Correlations between time estimations and mathematical intelligence have also been found (Kramer, Bressan, & Grassi, 2011). This connection remains whilst controlling for working memory and other executive functions. Other studies have found that mathematical ability itself predict performance on estimations of space and time as in numerical accuracy (Dehaene & Brannon, 2011).

Mathematical ability thus has a predictive power on the performance of dimension estimations. Such systematic connection suggests an interrelation that goes beyond simple behavioral associations.

Theories have been brought forth which posit a shared representational format that facilitate the associative qualities of these dimensions. The underlying representation is then processed as one of the respective dimensions by some mechanism.

Theory of Representation

*Mental Magnitude*

A prominent theory of common representation is that of mental magnitude. Such theories posit that space, time, and numbers are all, at their base, magnitude information for the brain. Dehaene and Brannon argued that from their findings that what facilitates mathematical cognition is that space, time, and numbers are fundamentally the same (Dehaene & Brannon, 2011). That is, they argue what is behind any mathematical thought is a representation of magnitude, and this includes considerations of space and time. Their studies have found that mathematical ability itself predict performance on estimations of space and time when they are represented numerically. Furthermore, giving spatial training to children seem to indicate an increase in their mathematical ability (Cheng & Mix, 2014), and correlations between time estimations and mathematical intelligence have also been found (Kramer, Bressan, & Grassi, 2011).

Since mathematical thought encompasses higher order manipulation of these dimensions, investigations into whether mathematical ability relies on a machinery of magnitude estimation has been speculated for quite some time.
In Stevens later work, he points out that all these dimensions are ‘prothetic’ in nature, that they are experienced as ‘more than or ‘less than’ (1975). Because of the precision and cross-modality of such continuous numerical assignment of subjective experience, he saw it that there had to be a common system which processed space, time, numbers, quantity, and other continua. However, what this system represents or how it works is not clear.

Modern experiments have tried to address this deeper question. They have expanded the method of magnitude estimation beyond subjective phenomena, applying it to the study of numerical cognition itself (Cantlon, Platt, & Brannon, 2009; Gallistel, 1989; Dehaene & Brannon, 2011). The work on magnitude estimations done by Stevens dealt with observable associations, either from the experimenter’s side or subjectively by the participant (1975). The work done by Cantlon et. al. suggests a cognitive association, that there is structures that specifically represent magnitude (2009). These structures also represent all the other dimensions (Cantlon, Platt, & Brannon, 2009).

The basis of numerical cognition is thought to be a type of number sense, known as a ANS (Approximate Number Sense) (Cantlon, Platt, & Brannon, 2009). The ANS is found in the intraparietal sulcus (IPS), and is involved in the approximation of the amount or size of discrete objects in a set.

Weber’s law is also present in the ANS (Cantlon, Platt, & Brannon, 2009). One of the standard operational tasks for the ANS is when participants are to judge which set of two contain more discrete objects. If a correct judgment is to be made in such a task, the difference needs to accommodate Weber’s law to facilitate detection. That is, the absolute difference between the two sets are not of importance. Rather the ratio between them is. Cantlon et al. concludes that what the ANS does is translate discrete objects into an analog magnitude representation. Weber’s law’s presence in the ANS further strengthen such a conclusion. That is, the ANS represent magnitude stimuli in a continous, predictable fashion.

Magnitude here is not used as a synonym for size. Nor is it a useful umbrella term for concepts that can be talked about as having size-like properties. Cantlon et. al. argues that the ANS activate functionally the same for space, time, numbers and other continua by virtue of them being magnitudes (Cantlon, Platt, & Brannon, 2009; Gallistel, 1989; Dehaene & Brannon, 2011). To further this point, Skagerlund and Träff (2014) demonstrated that children with DD
not only displayed impaired ANS functioning, but the same children also displayed difficulties in tasks involving space and time estimations. The ANS might thus be the hub which represents magnitudes.

**Behavioral Evidence of Mental Line Properties**

Another theory of common representation is the Mental Time Line Hypothesis (MTL) (Bonato, Zorzi, & Umiltà, 2012). This hypothesis is an extension of the classic finding that numbers seem to be represented along a mental line (ML), as a Mental Number Line (MNL). The proponents of the MTL hypothesis use the behavioral evidence for the MNL as backbone and extends it to the MTL, and even other continua that could be placed along a line.

Initial evidence for a mental number line (MNL) was first found in two performance effects in number tasks. One was the Distance effect (Moyer & Landauer, 1967). It showed that two numbers were harder to discriminate if they were closer together in magnitude. The other was the Problem-Size effect. It showed that two numbers which are larger in magnitude are harder to discriminate than two numbers of smaller magnitude (Restle, 1970). This effect remained despite the absolute difference, or distance, being the same between large and small magnitude.

The SNARC effect, the Spatial-Numerical Association of Response Codes, builds on the relative magnitude property that the Distance and Problem-Size effects demonstrate (Dehaene, Bossini, & Giraux, 1993). The SNARC effect demonstrated that smaller numbers were behaviorally responded to as being “to the left” of big numbers, as left responses were faster for small numbers located on the left side of space. Big numbers would be treated as being “to the right” for the analogous reason. Crucially, The SNARC effect demonstrates that numbers are represented sequentially in the brain at the behavioral level, serving as the primary evidence of a MNL.

Returning to the MTL, the main evidence which the MTL is based on is the STEARC effect, the spatial-temporal association of response code (Ishihara, Keller, Rossetti, & Prinz, 2008). Its’ operational definition is the same as SNARC, with the key difference being a spatial-temporal association. Similarly, to the MNL, the framework for the MTL is that time is posited to be organized along a mental line (Bonato, Zorzi, & Umiltà, 2012). Evidence suggest that days of the week, months, ‘past’ and ‘future’, and time-splices of objects that undergo change can be placed along a mental line.
The ML as a Magnitude Line

The MNL, and by extension, the ML, is thought to be present in the IPS which the same region the ANS is located (Bonato, Zorzi, & Umiltà, 2012). Cantlon et al. argue (2009) from their findings on the ANS that there is only one type of information that the ANS deals with. Joining these two facts, the ANS could thus contain either magnitude representation or a spatial representation of time and numbers. However, recent failures in replicating the SNARC effect cast doubt on whether the ANS do serve as a hub for spatial representation specifically. By crossing the hands associated with a left-right response, the SNARC effect could not be replicated (Wood, Nuerka, & Willmesa, 2006). A reversed motoric response should not, in theory, affect the results, as SNARC predict a spatial association to numbers. Further studies cast doubt on the SNARC effect being evidence of an MNL (Seppe & Gevers, 2008).

Traditionally the spatial location of a number on the theorized MNL is associated with the same spatial location of the response. Seppe and Gevers used a uni-manual approach instead, and with numbers being represented as either near or far. They demonstrate that although there was a spatial association to numbers, they cannot be directly placed on a mental line. They hypothesize that the MNL is mediated by a space-free representation of numbers first, a numerical magnitude. As the STEARC is based on the SNARC, these findings contest that only spatial representation is possible for the MTL, or any form of the ML. Other SNARC-like effects could thus serve as evidence for magnitude representations.

General Systems

There have been attempts to give a unifying explanation of how each specific dimension are connected to one another, with magnitude being the underlying representation. Such systematic explanations can be most readily found in the ATOM model.

ATOM

ATOM is a theory that addresses the multi-faceted interactions between space, time, and numbers is the ATOM (A Theory of Magnitude) (Walsh, 2003; Bueti & Walsh, 2009). Fundamentally, it posits that there is a common magnitude system which processes all the dimensions, but only partially (see fig. 2). It posits a shared magnitude system but allows for dimension-specific processes. However, for the system to allow for such interactions, the system is thought to be distributed throughout the brain.
Is Speed a Magnitude?

The Distributed System

ATOM posits that a common magnitude can be inferred (Walsh 2003, Bueti & Walsh, 2009). This inference is made by way of structural co-activation in the brain.

Posterior

Viewing more posterior regions, the parietal cortex is a crucial region of processing in the system. Structures within the parietal cortex are thought to be involved in the system. For example, parietal lesions causing hemispatial neglect not only makes patient neglect space on affected side, but also disrupt time estimation on affected side (Basso, Nichelli, Frassinetti, & di Pellegrino, 1996). Lesions to either left or right side of the parietal lobe causes asymmetrical deficits in number and spatiotemporal processing respectively (Niemeier, Stojanoski, & Greco, 2007).

Anterior

Anterior parts of the system is housed in the left temporal lobe and parts of the PFC (Walsh 2003). This region is thought to be involved in calculation, memory, and long-term planning. Single-unit recording of these regions in macaque monkeys show activation when spatial, numerical and temporal information is processed (Wilson, Scalaidhe, & Goldman-Racik, 1993; Nieder, Freedman, & Miller, 2002; Onoe, et al., 2001).
A Common Structure

All these findings emphasize the complex, and distributed nature of a potential magnitude system. Yet, the right inferior parietal cortex, in several of the above studies, is a consistently activated region (Walsh 2003, Bueti & Walsh, 2009). Thus, the IPC is the locus where the analog magnitude aspects of space, time, and numbers all coincide. This is further confirmed by theories that the ANS primary function is to represent magnitudes (Cantlon, Platt, & Brannon, 2009). This region is thus seen as the central hub where the common information structure of all dimensions is processed (Walsh, 2003; Bueti & Walsh, 2009). Once again viewing Fig. 2, this brain region could possibly be the intersection in the middle shared by all dimensions. Thus, the right IPC is a brain region that is a necessary component to the system. However, it is not a sufficient component to satisfy domain-general processing of all magnitude dimensions.

The Evolutionary Explanation for ATOM

ATOM sees the common magnitude system to be action-based. Space, time, numbers exist as parts and parcels because they are needed in action patterns that reach the same behavioral goal. The idea is that the dimensions recruit, and have been built up, by similarly integrated visuomotor programs in the brain. Therefore, the dimensions partially recruit the same structures, where a crucial structure is the right IPC. However, due to the co-activation of the PFC and the left temporal lobe in processing spatio-temporal information, magnitude can then be used for more exact estimation, judgment and action.

The posterior parietal cortex within the parietal lobe is the center-piece to ATOM. It is also involved in spatial attention (Purves et. al., 2013). In line with ATOM, the parietal cortex is less about “where”, and more “how” an action is to be performed in the world. Indeed, for spatial attention to function properly for any organism, a set of key abilities need to be possessed by the organism.

1. Performing any stimulus-driven behavior need to be performed correctly in space. That is, for proper interaction with the world, “how far” an object is in space, relative to the organism, needs to be known.

2. Time processing also need to occur for proper spatial attention (Bueti & Walsh, 2009). Take grasping for example. A creature needs to perform the computations necessary for
determining the spatial feature of the object to be grasped. But it must also compute the
duration, “how long”, that spatial feature will exist in a location the organism is paying
attention too. As the organism moves, the objects its’ visual field changes. The location of
objects in space change as a function of time. To not grasp too early, or too late, “how long”
an object will be present needs to be computed.

3. Similar behavioral goals, as to that of space and time, is present in contexts where
processing of quantity is of importance (Walsh, 2003). In determining the spatial location of
an object, another necessary computation that must be performed is “how many” there are of
said object. A fast and frugal estimation of the amount of tree branches in a location might be
needed if said action will have a chance to succeed. Action-based Interference studies done by
Fias et al. (2001) has shown that when digits are presented before a spatial-orientation
judgment, the judgement is influenced by the preceding digit. However, for a color judgment
that demands less parietal involvement, the preceding digit had no effect.

The inferior parietal cortex, where the ANS can be found, is integral for quantity and numeric
estimation. Walsh and Bueti argue (2009) that such findings make sense in ATOM from
phylogenic standpoint. The inferior parietal cortex is where the analog, sliding nature of the
world is thought to be processed. Computations such as: “more than-less than”, “smaller-
bigger”, and “nearer-farther” are what is relevant here. These analog systems served well for
establishing an approximate number system and numerical cognition.

So the possible hierarchy might thus be:

1. The parietal cortex is for “how” an action is done in the world.
2. The posterior parts are here more concerned with how attention is directed in that context.
   “how” here becomes a question of “how many”, “how much”, “how far”, and “how long”
   something should be attended.
3. In that context, the IPC/IPL is where the exogenous, analog, magnitude information is
   processed.

Walsh (2003) articulates a Piagetian argument related to this in that babies might possess an
undifferentiated magnitude system at birth. Then, when the baby interacts with its’
environment, it learns to differentiate time, size, quantity, space in a statistical fashion.
The magnitude system starts to further differentiate these dimensions, it becomes more distributed, relying more and more on specialized, overt processing.

Speed as a Dimension

Walsh also includes speed here as possible dimension in the precursor, undifferentiated system. ATOM, however, does not address this dimension. This might be due to the common-sense assumption that if speed is included in the magnitude system, it is assumed to be an interaction between space and time.

Although this assumption is not incorrect, it might not capture how speed is estimated and judged in psychological reality. Speed, by definition, is the relative velocity an object is moving to a reference. This can thus be assigned a numeric value. In this sense, speed might be another dimension that could be incorporated in a more comprehensive version of a common magnitude system.

To establish speed as a distinct dimension in ATOM, the first question one needs to ask whether estimations of speed are distinct from a combined estimation of time and space. There is evidence to suggest this. There is evidence that children do infer speed from distance and time, albeit in a simplified manner (Wilkening, 1981). However, speed as distance divided by time do not seem to be computed simply as such. When participants are evaluated on their understanding of speed through judgment tasks, 5-year-old simplify speed=distance/time to a distance-only rule. Older age groups do make more accurate judgments in actual speed, as they consider time as a crucial variable. Yet, they still simplify slightly by using a speed=distance-time rule. This suggest that speed is connected to space and time behaviorally, but not necessarily as a strict computation of the two.

The flip side to these heuristics are the possible biases that might arise. One such bias is known as “representation momentum” (Thornton, 2002). When an object enters a tunnel, the object is hidden from view. Participants must use an imagined representation of where that object is inside the tunnel and press a button when they think it hits a wall. The findings show that shift the object slightly forward, thus mislocating the object’s impact as being beyond the wall. This is so because the representation of the actual speed is thought to gain momentum once it is hidden from view.
Speed as a Magnitude

Speed as an Action-Coded Dimension

Representational momentum might have served an evolutionary purpose. Freyd posits that dynamic representations like representational momentum exist because of the adaptive behavior they provide (1992). It is better to err on the side of thinking a predator will pick up speed, slightly accelerate, rather than to maintain or diminish in speed once it is occluded. This increase the chances of a swifter escape, sacrificing accurate speed estimation for adaptive action.

Such built in bias suggest that there is some primary mechanism that informs speed estimation. Several key-points suggest that this mechanism is within a larger system.

1. Dynamic representation of speed exists and is there to facilitate adaptive action. This suggest speed having its own unique representation to facilitate appropriate action.
2. This action-boundedness of speed estimation is similar to that of the other dimensions within the ATOM framework.
3. Accuracy of speed estimation improves over development.
4. This is possibly due to the better integration of speed representation with the representations of space and time.
5. This is possible because speed is yet another domain specific dimension within ATOM along with space, time and numbers.

Although Bueti and Walsh do not go into detail speed’s subsumption in ATOM, they do mention “how fast” is a crucial consideration in catching something (Bueti & Walsh, 2009). To reiterate, the real job of the parietal cortex is not necessarily to handle “where” computations relevant for action (Walsh, 2003). The real function is to compute aspects of the environment that are “how far”, “how many” and “how long” with respect to action. Among these computations, “how fast” might also one of the computations the parietal cortex needs to perform.
Operationalizing Speed As a Magnitude

Firstly, the “how” aspects of speed could be found in the posterior parts in the parietal cortex. It is reasonable to presume the dynamic representations that inform action is possibly handled in this area.

Secondly, in the more anterior parts, static representations of speed, such as motion perception, which is located more in the temporal areas such as V5 (Bueti & Walsh, 2009). Here, “what” is moving, or detection of motion, is the important consideration (Purves, et al., 2013).

Following these two facts, two conclusions follow. When speed estimation is performed once the stimulus is occluded, no motion perception can occur. Therefore, the representational mechanism of speed might be located the posterior parts of ATOM in the parietal region.

However, the anterior do serve a part in ATOM, as was the case for time and numbers (Bueti & Walsh, 2009). These regions are involved in static and discrete aspects of time, speed and quantities. These are thought to have evolved from the more continuous aspects found the posterior parts of ATOM. What is of interest here is that the discrete aspects of speed, motion processing, seem to prime other magnitude processes (Bueti, Walsh, Frith, & Rees, 2008).

Walsh (2003) further argues from this relationship that any spatially and action-coded magnitude will yield a relationship between magnitude and space, and this priming effect would be present for a host of magnitude dimensions, including speed. The prediction is that the SNARC effect, and by extension the STEARC effect, are in fact both examples of SQUARC effects within the ATOM framework. SQUARC stands for spatial quantity association of response codes. It posits that any magnitude, represented discreetly, can be placed along a continuous spatial line.

As mentioned, ATOM already emphasizes speed as an action-based magnitude within its’ theory (Bueti & Walsh, 2009). However, there has not been many studies demonstrating that speed is, in fact, a kind of magnitude. If speed possesses both static, discrete representations by way of motion, and dynamic representations, speed could be tested within a SQUARC framework. The discrete representation should prime a dynamic representation of speed in a magnitude or spatial context. There is already evidence of dimensions other than space, time, and numbers exhibiting SNARC-like effects, such as pitch (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), and ordinal position (Gevers, Reynvoet, & Fias, 2003). The
findings on ordinal position are especially important since speed can be represented as values which follow ordinal position.

This would thus suggest that speed has testable connection to time, space, and numbers as a magnitude. Furthermore, if the SNARC effect is present for speed, that would suggest that the Problem-Size effect might also be present for speed. The SNARC effect suggests that speed can be placed on a “mental speed line”, where low speed values are thought to be located to the left of the line and high speed values are located to the right. The Problem-Size effect has been taken as evidence for mental number lines (Restle, 1970). If the Problem-size effect is present for speed, this might serve as further evidence for speed being a type of magnitude. Problem-size effects have also been shown to have a connection to magnitude processing (Zbrodoff & Logan, 2005). Present studies on the Problem-size effect with arithmetic tasks show that the larger the total magnitude of two numbers are on an arithmetic task, the greater the increase in response time when solving that task, and this change in response time is linear with respects to increases in numerical magnitude. 7+6 will thus take longer to solve than 2+3, even though the distance between the numbers is the same. This effect allows the possibility to examine whether speed can be further connected to functional characteristics of magnitudes.

Two research hypotheses and corresponding operational hypotheses arise from this reasoning, which this experimental study investigates.

1. Is there evidence of a SNARC effect in speed estimation?

Given that the Mental Number Line organizes numbers in a left to right direction, and that the SNARC effect is present in left to right response selection, if correct judgments about differing speed values require the use of a magnitude processing system, in a SNARC condition where correct response selection is determined by correct judgments of the magnitude of speed values, one would expect participants to have a shorter response time when faster speeds are spatially located to the right, and lower speeds to the left compared to the reverse. Since faster response time indicates the ease of discrimination between the two speeds, faster response time would have to coincide with the left-right response association to a ‘mental speed line’ according to the SNARC effect. This spatial organization of speed along such a line would indicate that speed is governed by a magnitude processing system as the SQUARC effect predicts.
2. Is there evidence of a Problem-Size effect in speed estimation?

The reasoning here is the same. If the Problem-Size effect is present on a left-right response selection task where the stimuli’s Problem-Size conform to the difference in speed values, one would expect correct responses to be faster when the Problem-Size is small, and correct responses to be slower when the Problem-Size is larger. The Problem-Size effect would thus only be present for speed if speed could be placed along a ‘mental speed line’, which would indicate that speed is governed by a magnitude processing system as the SQUARC effect predicts.
Method

Design
The experiment used a within-subjects design.

Apparatus
Stimuli were presented on a laptop computer screen (Lenovo) with a pixel resolution of 1280 by 720 pixels. The screen had a height of 19.4 cm and 34.5 cm width that was viewed from a distance of about 60 cm by the participant. From these three metric values, speed of the moving stimuli could be calculated. Slow speed values were 1-4 deg/s in the first hypothesis and 1-6 deg/s in the second, and Fast speed values were 6-9 deg/s in the first hypothesis and 8-13 deg/s in the second. The moving stimuli were two small (0.6 deg diameter) circles, one red and one yellow. The stationary stimuli, a barrier, 18 deg vertical, 0.25 deg horizontal in size and had small (2.5 deg horizontal 0.25 deg vertical) horizontally oriented arms attached to it on both sides. The red circle moved from the participant’s left to right towards a vertically oriented green barrier in the center of the screen, whilst the yellow circle moved from the observer’s right to left towards the same barrier. Responses were recorded with a keyboard.

Fig. 3. Visual display of the Race-To-Wall test (RTW) and Problem-Size test (PZ). The visual design of the two experiments have been adapted from (Gray & Thornton, 2000)
Test battery
The test battery contained 10 tests in total, where 2 were used for this study (corresponding to each construct being measured). Considering the 8 tests not included in this study, some of these tests involved making perceptual and cognitive estimations of time and space, others involved making mental rotations and magnitude estimations, and tests for numeracy an arithmetic fluency. It is finally worth noting that the two speed tests that are used in this study were performed first in the test battery, so it is reasonable to conclude that no other test influenced the outcome of the speed tests.

Race-to-Wall (RTW)
This test was used to investigate the SNARC effect. The independent variable was the speed of the stimuli separated into two conditions: Slow-Fast and Fast-Slow, where the order indicates the location of the Fast stimuli or Slow stimuli either moving from the left or the right side of the screen towards the center. In the Slow-Fast condition for example, in any given trial the Slow stimuli would be located on the left side and move to the right towards the wall, and the Fast stimuli would be initially located on the right and move to the left towards the wall. The Slow stimuli were operationalized as stimuli which moved at a speed of 1-4 degrees per second, and the Fast stimuli as stimuli which moved at a speed of 6-9 degrees per second, and 11 and 13 deg/s. Each participant was exposed to both conditions, where each condition was evenly distributed in a random sequence across a total of 80 trials.

The participants’ task was to discriminate as fast as possible which circle was moving faster towards the barrier, i.e. which circle will first make contact with the barrier. If the red circle on the left side of the barrier would first make contact, the correct response would be made by pressing the A key on the keyboard, corresponding to the left side. If the yellow circle on the right side would first make contact, the correct response would be made by pressing the L key on the keyboard, corresponding to the right side. After a verbal instruction of the task had been given to the participants, they were shown an image of the visual display of the stimuli used in the test for further clarification and given further information how their performance would be evaluated in terms of correct discrimination and response time. The RTW task was then setup. 15 degrees from the barrier were used for both circles, and the available speed values was set-up to vary among from 1-9 deg/s for all participants, some also had 11, 13 deg/s. The test began by the participant pressing enter on the keyboard.
To ensure that a correct discrimination could be discerned in any given trial, the assignment of speed values were partly restricted so that the circles could never attain a speed equal to the other in a given trial. Response time in milliseconds and correct discrimination is recorded for each trial. The Race-To-Wall test took about 4 minutes to complete for each participant.

**Problem-Size (PZ)**

This test was used to investigate the Problem-Size effect. The independent variable was also the speed of the stimuli separated into two conditions: Small Problem-Size or Big Problem Size for both moving stimuli. Small Problem-Size was defined by the minimum speed value both stimuli could be assigned, which were 1-4 deg/s. For Big Problem-Size, the maximum speed value both stimuli could be assigned were 6-9 deg/s with some participants also being exposed to 10-13 deg/s. Each participant was exposed to both conditions, where each condition was evenly distributed in a random sequence across a total of 80 trials. This was to ensure that all participants were exposed to the same number of Small and Big Problem-Size conditions so that the test was uniform in difficulty between the participants.

Some rules for the speed assignment was like that of RTW as well. The yellow and red circles could never attain a speed equal to the other in each trial.

In PZ, the crucial difference from RTW is the way the speed values are set-up for the circles and ordered among the trials. The absolute difference between the speed of the red and yellow circle has been manually chosen by the experimenter, according to the Problem-Size effect. This was done by choosing a maximum set of differences between the speed of the yellow and red circles. If a set of {2, 3, 4} was used, no absolute difference in respective speed of the circles could ever be larger than 4, or lower than 2. Practically, if speeds of 1-9 deg/s were used for some trials, a speed of 6 could never be paired with a speed of 1 or 5 in any of those trials, since this was outside the scope of allowed absolute difference in speed between circles. For the majority of participants, a set of {2, 3, 4} was used as absolute differences among all trials. Some were however exposed to a bigger set of {2, 3, 4, 5}. However, it was also ensured that any pairing of two speeds was mirrored in some other trial. Response time in milliseconds and correct discrimination is recorded for each trial.

The visual characteristics of the test were the same as those of the RTW test (See Figure 1).
Participants were instructed that the test, visual display, and task at hand would be the same. If the red circle on the left side of the barrier would first make contact, the correct response would be made by pressing the A key on the keyboard, corresponding to the left side. If the yellow circle on the right side would first make contact, the correct response would be made by pressing the L key on the keyboard, corresponding to the right side. The experimenter informed them however that the main difference in this test that some values had been modified. The available speed values were set-up to vary among from 1-13 deg/s for all participants. The Problem-Size test took about 4 minutes to complete for any given participant.

**Ethics**

One could argue that performance tests where ability can vary significantly between participants can cause harm to self-esteem for participants who perform poorly, as evidence of poor performance cannot be hidden from the participant if they were to ask for it. This would include evidence of either extremely good or extremely bad performance. However, since such occurrences are not outside the scope of daily life, where performance is continually evaluated in a range of tasks in school and in work, one could concede that harm to self-esteem can be neglected as a valid ethical consideration. More information about what the actual research entailed was given more explicitly during this debriefing period. This was done to ensure that the data would not contain any preconceived notions of what the correct response would look like for any given trial. This act of omission can be argued as a form of deception, but the more comprehensive nature of the study was given after completion, so the omission was only temporary.

**Procedure**

15 students from Linkoping University participated in the study (3 females and 12 males). The age ranged from 20 to 33 years old with an average of 24.86 (SD = 4.02). The participants were selected out of convenience and were given a movie ticket as compensation for their participation.

Before the experimental procedure began, the participant was informed that the nature of the whole experiment with all 10 tests entailed investigating whether a certain measure could be encapsulated within magnitude processing and mathematical ability. They were then given
further information regarding what the individual tests entailed. They were then informed of the total time of the whole procedure, as well as how many tests were to be performed, and that these tests varied in time and difficulty. The participants were also informed that they had the option to end the procedure at any time. If they agreed to all of this, their full consent was given by way of signature. They were informed that their data would be used anonymously in the research report.

After the experimental procedure had been completed, the participant was debriefed of the explicit purpose of the study and was also given an overview of their test performance. More information about what the actual research entailed was given more explicitly during this debriefing period.

The whole experimental procedure took about 1 hour and 15 minutes to complete for each participant. The first task in the relevant test battery was a Time-to-Collision task where a ball was moving towards a wall and the participant had to estimate when the ball made contact with the wall after a disappearance point. Then, the two tests relevant for this study commenced. First, the Race-To-Wall task was performed, then the Problem-Size task was performed by the participant.

**Data Analysis**

A paired-samples t-test was used for both the RTW test and the PZ test, using the within-subject conditions as the independent variable in all analyses. In the RTW test, all speed values above 9 were omitted, as well as pairs that contained speeds of 5 deg/s to have even and non-overlapping conditions. For the PZ test, all speed values were used except ones containing 7 to have two separate, non-overlapping conditions. In both tests, an average response time was calculated for each of the 15 participants for each separate condition. T-tests performed were one tailed since both hypotheses were uni-directional.
Results

SNARC

The mean response time for the Slow-Fast condition, IV-level 1, was 652.57 milliseconds (SD = 167.57). For the Fast-Slow condition, IV-level 2, the mean response time was 655.47 milliseconds (SD = 156.30). There was no significant difference in the mean response time for the two conditions; t(14) = 0.13, p = .450 (one-tailed), $d: 0.033$.

![SNARC Chart]

Problem-Size

The mean response time for the Low Problem-Size condition was 850.37 milliseconds (SD = 427.13). For the High Problem-Size condition, the mean response time was 679.78 milliseconds (SD = 216.05). There was a significant difference in the mean response time between the High Problem-Size and the Low Problem-Size condition, but in the opposite direction of the hypothesis; t(14) = -2.65, p = .019, $d: -0.529$. 
Is Speed a Magnitude?

Discussion

The general findings of this experimental study can conclude that neither the SNARC nor the Problem-Size effect was present during speed estimations. In fact, the results gained from the Problem-Size test indicate that the reverse of the predicted effect is present for speed estimations. Therefore, speed estimations do not display any characteristic evidence for being a magnitude along with time, space, and numbers. The poor results might be due to general methodological difficulties. In the SNARC test, the conditions used for finding the SNARC effect was only applied post-hoc. That is, the test itself had no conditions applied beforehand to restrain the speed values between the two stimuli in accordance with the SNARC effect, so that over 80 trials for each participant, the speed value for one stimulus could vary randomly, unconditionally to whatever speed value the opposing stimuli had been assigned. This meant that there only 15-35 trials could be used for each participant which followed the conditions, and the separation of trials into a Slow-Fast condition and Fast-Slow condition had to exclude all trials that did not follow the rules of the two conditions. Since less than the total data points could be used for determining each participant’s average response time in each condition, the reliability of the data comes into question. Secondly, due to inconsistent use of available speed the stimuli could attain due to experimenter error, not all participants were exposed to exactly
the same speed values in total. Since some were also exposed to speed 10-13 deg/s, This meant that some participants had more difficult trials due to the faster speed. Furthermore, this also meant that these participants were not exposed to as many speed values which were in the proper range of 1-4 and 6-9 deg/s, since all participants had to make estimations for 80 trials each. This meant that even fewer trials could be used for them, decreasing the reliability of the test. Lastly, even if one were to exclude these participants from the study, there was no guarantee for any of the participants that the two conditions would be balanced, since the distribution of trials was completely random, and again, only a select few of the 80 trials were actually in accordance with the conditions. This effectively meant that some participants only had 5 trials in the Slow-Fast condition to base their response time on, and other participants had up to 18 trials from which to calculate their response time.

For the Problem-Size effect, the significance and large effect size can be accounted for more reliably, since the construction of the test itself meant that many more trials could be used to calculate a participant’s mean response time, thereby moving much closer to the true mean.

There were procedural problems here as well. Some participants were given more speed values from the high condition among the 80 trials, and some participants were exposed to easier trials due to higher absolute differences, i.e. {2, 3, 4, 5}, within conditions. Why this effect is the opposite might have to do with the construction of the test and test environment. Due to the nature of the test, both conditions were difficult to accurately estimate which speed was faster in any given trial at the very start. To counteract this, participants could wait until the stimuli moved closer to the wall were a distance judgment could be used instead to determine which stimuli would first make contact with the wall and was, therefore, moving faster. Since in the Big Problem-Size condition both stimuli moved towards the wall faster, a distance estimation strategy was available more readily, which in turn made their response time faster. If one assumes that the test and testing environment is reliable, small Problem-Sizes, or slow speeds, are simply harder to discriminate than when discriminating fast speeds. This would go against the proposed hypothesis that correct speed estimation is simply a matter of comparing the magnitude of space and time and computing the differential. If one would assume the Problem-Size test was reliable, it is possible that correct speed estimations might be more easily processed and determined when there is a high-to-low ratio of distance to time.
Future Research

In future research for the SNARC effect in speed estimations, what speed values are more relevant to the SNARC effect, and with a clear separation of the SNARC conditions within the test environment itself, could be investigated. Future research for the Problem-Size effect in speed estimation might vary the distance between the moving stimuli within and across trials to counteract the distance heuristic. For both tests, low sample size and few data points for each participant’s test result might have produced the non-significant results regarding the hypotheses tested, and future experiments which counteract the present flaws in methodology might produce new, significant findings.

Conclusion

There was no significant difference for the SNARC effect in speed estimations. There was a significant effect for tests of Problem-Size in speed estimations, but the effect was in reverse direction. Therefore, the null hypothesis for both questions cannot be rejected. Future research might investigate how other methodological decisions and tests might affect the results.
References


