Social Cueing of Numerical Magnitude

Observed Head Orientation Influences Number Processing

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Summary

In many parts of the modern world, numbers are used as tools to describe spatial relationships, be it heights, latitudes, or distances. However, this connection goes deeper as a myriad of studies showed that number representations are rooted in space (vertical, horizontal, and/or radial). For instance, numbers were shown to affect spatial perception and, conversely, perceptions or movements in space were shown to affect number estimations. This bidirectional link has already found didactic application in the classroom when children are taught the meaning of numbers. However, our knowledge about the cognitive (and neuropsychological) processes underlying the numerical magnitude operations is still very limited.

Several authors indicated that the processing within peripersonal space (i.e. the space surrounding the body in reaching distance) and numerical magnitude operations are functionally equivalent. This assumption has several implications that the present work aims at describing. For instance, vision and visuospatial attention orienting play a prominent role for processing within peripersonal space. Indeed, both neuropsychological and behavioral studies also suggested a similar role of vision and visuospatial attention orienting for number processing. Moreover, social cognition research showed that movements, posture and gestures affect not only the representation of one's own peripersonal space, but also the visuospatial attention behavior of an observer. Against this background, the current work tests the specific implication of the functional equivalence assumption that the spatial attention response to an observed person's posture should extend to the observer's numerical magnitude operations.

The empirical part of the present work tests the spatial attention response of observers to vertical head postures (with continuing eye contact to the observer) in both perceptual and numerical space. Two experimental series are presented that follow both steps from the observation of another person's vertical head orientation (within his/her peripersonal space) to the observer's attention orienting response (Experimental series A) as well as from there to the observer's magnitude operations with numbers (Experimental Series B). Results show that the observation of a movement from a neutral to a vertical head orientation (Experiment 1) as well as the observation of the vertical head orientation alone (Experiment 3) shifted the observer's spatial attention in correspondence with the direction information of the observed head (up vs. down). Movement from a vertical to a neutral end position, however, had no effect on the observer's spatial attention orienting response (Experiment 2). Furthermore, following down-tilted head posture (relative to up- or non-tilted head orientation), observers generated smaller numbers in a random number generation task (range 1- 9, Experiment 4), gave smaller estimates to numerical trivia questions (mostly multi-digit numbers, Experiment 5) and chose response keys less frequently in a free choice task that was associated with larger numerical magnitude in a intermixed numerical magnitude task.

Experimental Series A served as groundwork for Experimental Series B, as it demonstrated that observing another person's head orientation indeed triggered the expected directional attention orienting response in the observer. Based on this preliminary work, the results of Experimental Series B lend support to the assumption that numerical magnitude operations are grounded in visuospatial processing of peripersonal space. Thus, the present studies brought together numerical and social cognition as well as peripersonal space research. Moreover, the Empirical Part of the present work provides the basis for elaborating on the role of processing within peripersonal space in terms of Walsh's (2003, 2013) Theory of Magnitude. In this context, a specification of the Theory of Magnitude was staked out in a processing model that stresses the pivotal role of spatial attention orienting. Implications for mental magnitude operations are discussed. Possible applications in the classroom and beyond are described.

Contents

1 | General Introduction

Look at the photograph below (see Fig 1). If I ask you how many jewels might be attached to the objects in the showcase, you will most probably start to ponder about their quantity. In the end, however, you will rather give me a numerical estimate off the top of your head than trying to count and interpolate the exact number. Indeed, in the context of the present thesis, the metaphor "off the top of your head" might describe the estimation process in your head rather appropriately. For the results of numerical cognition studies indicate that your numerical estimate might be smaller or larger depending on your vertical head orientation (Winter & Matlock, 2013). Specifically, spatial orienting information like "down" might indeed activate the associated quantity code "small", which in turn might affect the magnitude of your numerical estimate based on the spatially oriented representation of numbers and quantity (e.g. Dehaene, Bossini, & Giraux, 1993). Taking a step further, the present research suggests that even observing someone else's spatial head cues should not only trigger an attention orienting response in perceptual space, but also bias the magnitude of one's numerical smaller-larger-operations.

Figure 1. Photograph of the showcase, in which the royal regalia of Hungary are displayed (©Piotr Przemysław Karwasz, CC-BY-SA 3.0).[1]

We encounter the spatial mapping of numerical magnitude on a day-to-day basis in our cultural environment. For instance, we use numbers as a tool to describe heights, lengths, and distances, for example when we mark flood water levels on buildings along rivers, indicate the width of bridges on signs along the motorway, or the space that separates us from the next village, town, or city. In reverse, we use space to communicate the magnitude of numbers, be it in clocks, all kind of graphs (for example symbolizing the number of a country's inhabitants relative to others), or the number line that is used to

[1] Photograph by Piotr Przemysław Karwasz, modified by Alvaro qc, Wikimedia Commons, distributed under a CC-BY-SA 3.0 license, URL: https://creativecommons.org/licenses/by-sa/3.0/

teach children the meaning of numerical magnitude at school. From a numerical cognition perspective, especially the latter observation is of significance as even preschool children displayed a magnitude bias on a spatial task that reflected a horizontal mapping of non-symbolic quantity on horizontal space (similar to that of schoolchildren and adults; see de Hevia & Spelke, 2009). Moreover, a recent study indicated that only preschool children that displayed a consistent spatial mapping of numbers were able to compare digits by numerical magnitude (Sella, Berteletti, Lucangeli, & Zorzi, 2017). Thus, understanding the magnitude behind the number seems deeply rooted in spatial-numerical associations (e.g. Booth & Siegler, 2006; Dehaene, Piazza, Pinel, & Cohen, 2003; Dehaene, 2011), which in turn might be a valuable resource for math educational programs - from teaching young children arithmetic up to trainings for children suffering from dyscalculia (Dehaene, 2011).

In spite of its significance for mathematical education, however, we are only beginning to understand the nature of the mechanisms underlying numerical magnitude operations like smaller-larger judgments or addition. Therefore, the current research hopes to shed some light on this matter by elaborating on the idea that numerical cognition shares functional features with the multisensory-motor mapping of space within reaching distance (e.g., Lohmann, Schroeder, Nuerk, Plewnia, & Butz, 2018; Longo & Lourenco, 2010). This region immediately surrounding the body is called peripersonal space (the term was introduced by Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981a, b) and serves as interface for the interaction with objects and others (e.g., Brozzoli, Makin, Cardinali, Holmes, Farne, 2011; Holmes & Spence, 2004). Crucially, even viewing changes in someone else's orienting behavior - pertaining to her/his peripersonal space - was shown to cue an observer's attention orienting behavior to the same direction (e.g., Frischen, Bayliss, & Tipper, 2007). In this context, the present thesis aims at addressing the question if the peripersonal space behavior of others extends to the numerical magnitude operations of an observer via social cueing. For this purpose, I will proceed as follows: In the remainder of this chapter, I will briefly outline the status quo of research on mental number representation in general and the role of spatial-numerical associations in particular. In the following chapter, I will analyze past research, beginning with behavioral manipulations that were shown to affect the processing of numerical magnitude (with emphasis on vertical spatial-numerical associations). In this context, I will discuss the possible role of plurimodal spatial attention orienting of peripersonal space as common underlying mechanism. In the next chapter, I will discuss the implications of the functional equivalence assumption for the observation of someone else's peripersonal space behavior. Then, I will briefly review the relevant social cueing theory and research (again with emphasis on vertical spatial attention orienting. Finally, I will outline the studies included in the present thesis, which combined social and numerical cognition to show that (A) observing others' static vertical head positions result in vertical attention shifts (Experiments 1-3), (B) which in turn extend to the magnitude of observer's numerical operations (Experiments 4-6).

1.1 Representing numerical magnitude

1.1.1 From number perception to number representation

Numerical cognition is rooted in perceiving the number of a set of objects in the environment intuitively, for example when grasping the number of objects in a showcase (see Fig. 1). This *number sense* allows us to recognize changes like additions or removals in the said quantity of objects (i.e., *numerosity*) immediately (Dantzig, 1967/2007; Dehaene, 2011). Interestingly, when being confronted with small quantities of up to four objects (e.g. the number of objects displayed in the showcase), humans make fast and exact enumerations (a process called *subitizing* for the range 1-3; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982), presumably relying on an multiple object tracking system (e.g., Trick & Pylyshyn, 1994; Spelke & Kinzler, 2007) rather than counting (e.g.; Dehaene & Cohen, 1994). By contrast, when being confronted with larger quantities of objects (e.g. the number of jewels attached to the objects in the showcase) humans seem to rely on an *Approximate Number System (ANS)* for numerosity estimation (e.g. Halberda & Feigenson, 2008; for an overview considering both systems, see Feigenson, Dehaene, & Spelke, 2004). Research suggested that a number sense is not only present in humans (from early infancy; Feigenson et al., 2004), but also in several nonhuman animals like fish (Agrillo, Piffer, Bisazza, & Butterworth, 2012) and chicken (Rugani, Vallortigara, Priftis, & Regolin, 2015), supposedly for the purpose of comparison (where to find more food, less predators, etc.; Dehaene, 2011). In spite of its merits, however, the ANS's estimate input to numerical magnitude processing is imprecise (e.g., Whalen, Gallistel, & Gelman, 1999) and easily malleable (for example via calibration; Izard & Dehaene, 2008).

In a similar vein, when listening to a number word sequence (e.g. sixty-five) or reading its Arabic numeral (at least in the Western hemisphere at the present time), we immediately retrieve its non-symbolic quantity representation, which contains the number's semantic magnitude information (Dehaene, 2011). The *Triple Code Model* of number representation (*TCM*; Dehaene, 1992; Dehaene & Cohen, 1995) is dedicated to input-output as well as such internal translation processes between auditory, visual, and analogue number representation formats. Moreover, the TCM assigns numerical abilities to three types of representations: (1) learned numerical knowledge like counting and the multiplication table to the symbol-based *auditory code*; (2) digit processing such as in parity judgment to the symbol-based *visual code*; (3) numerical magnitude processing like smaller-larger judgments to the non-symbolic *analogue code*. Thus, TCM predicts that output can only occur in form of the two symbolic codes (spoken number word, written number symbol or word). Nonetheless, symbolic codes are meaningless unless associated with their non-symbolic analogue magnitude code (Dehaene, 1992).[2] Evidence for an

[2] Please note that TCM (Dehaene, 1992) makes assumptions on input formats (symbolic vs. verbal vs. numerosity), but not modalities. For instance, an auditory input can be either a symbol (e.g., someone saying „five") or a numerosity (e.g., five sounds in a row like tok-tok-tok-tok-tok).

automatic link between number symbols and their analogue quantity representation comes - amongst others - from multi-digit studies (cf. Dehaene, 2011). In one of these studies, participants had to decide whether two-digit numbers between 31 and 99 are smaller or larger than 65. In line with the *distance effect* (we come to that at a later point), response times increased continuously with proximity and - crucially - irrespective of differences in decimals (e.g. 59 vs. 60; Dehaene, Dupoux, & Mehler, 1990). This result suggests that humans process multi-digit numbers holistically as if they were numerosities rather than serially, i.e. digit-by-digit, like in a computer program (Hinrichs, Yurko, & Hu, 1981). Moreover, this finding brings us back to my initial argument that numerical cognition is rooted in perceiving quantities of objects.

In sum, past research showed that both number symbol and numerosity perception result in the mental (co)activation of an analogue numerical magnitude code, which is presumably in charge of numerical magnitude operations like approximation and comparison (Dehaene, 1992). Crucially, both the Approximate Number System (ANS) and the TCM allow for the prediction that analogue number representation (roughly) follows Weber's law (Libertus & Brannon, 2009; for a methodological review on ANS research, see Dietrich, Huber, & Nuerk, 2015), which will be described in the next section. Beyond cognition, both lines of research make predictions addressing the neuroarchitecture of a mental number representation (regarding ANS, see e.g. Roitman, Brannon, & Platt, 2007; regarding TCM, see e.g. Schmithorst & Brown, 2004). Thus, theory and research on number perception address both the questions *where* numerical cognition takes place and *which* organizational principles it follows.

1.1.2 The mental number line

The notion of a *mental number line* was introduced to describe the imagery analogue system for the cognitive representation of magnitudes and/or their numerical symbols along a continuous domain (Moyer & Landauer, 1967; the metaphor, however, was first introduced by Restle, 1970). The organizational feature *continuous* (rather than discrete, stepwise) means that the activation of one number representation on the mental number line (e.g., four objects in the showcase) co-activates neighboring numbers (i.e., three and five), those neighbors' neighbors (i.e., two and six) and so on. However, the extent of co-activation decreases with the distance to the originally activated number (cf. Gilmore, Göbel, & Inglis, 2018). Therefore, accuracy and speed participants' responses in a number comparison task increase with semantical distance (*distance effect*; e.g., Moyer & Landauer, 1967). On a neural level, the Approximate Number System supposedly translates the perceived discrete quantity input into continuous analogue magnitudes with the help of number-sensitive neurons. In this context, the shape of the representation of the number on the mental number line (as well as the tuning curve of the respective neuron; Nieder & Miller, 2004) follows a Gaußian distribution that overlaps with those of neighboring numbers (and so on), which is the reason for the co-activation (cf. Gilmore et al., 2018; Dietrich et al., 2015).[3]

A second essential feature of the mental number line pertains to its shape. Many authors compare it to a compressive, logarithmic-like continuum allocating more space to smaller and less to larger numbers (and/or numerosities), rather than to an equally spaced ruler (e.g., Dehaene, 2003; Dehaene & Changeux, 1993; Dehaene et al., 1990).[4] Originally, this shape was derived from the pattern of response times and errors found in single-digit number (Moyer & Landauer, 1967), multi-digit number (e.g., Hinrichs et al., 1981; Pinel, Dehaene, Riviere, & LeBihan, 2001), and non-symbolic quantity (e.g., van Oeffelen & Vos, 1982) comparison tasks. Specifically, participants' acuity in these tasks depended on the ratio of the numbers that had to be compared: The larger the overall magnitude (*magnitude effect*), the less accurate and slower were the responses of participants (e.g., Moyer & Landauer, 1967). Later, the results of neuroimaging research supported the proposed logarithmic-like distribution of number representation empirically (e.g., Nieder & Miller, 2003; Roitman et al., 2007).[5]

A third crucial feature of the mental number line is its supposed intimate link with spatial cognition. To illustrate this bidirectional association between numbers and space, the mental number line was complemented with spatial directionality (e.g., Dehaene et al., 1993). In its modern version, a small number is represented by a coding of a low (or left) position, while a large number is represented by a coding of a high (or right) position (e.g. Winter, Matlock, Shaki, & Fischer, 2015). Thus, the mental number line outlines the organizational principles of the mental number line. However, it remains silent in terms of the underlying mechanism, or, in other words, the question *how* numerical magnitude is operated.

1.1.3 Association between numbers and space

Experimental evidence for a spatial coding of numerical magnitude originates in the so-called Spatial-Numerical Association of Response Codes (SNARC) paradigm (Dehaene et al., 1993; for a review see Wood, Willmes, Nuerk, & Fischer, 2008). In the vertical version of the SNARC paradigm, participants solving an unrelated parity judgment task

[3] In monkeys, the activity of number-selective neurons in the ventral intraparietal sulcus (VIP) reached a peak in response to a particular numerosity, was reduced in response to similar, and vanished in response to distant numerosities (Nieder & Miller, 2004).

[4] Please note that some studies suggest a gradual evolution of the mental number line from logarithmic to a linear shape due to mathematical education (e.g., Halberda & Feigenson, 2008; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Opponents of this view suggest linearly organized numerical magnitude codes that expand to ever larger number ranges due to mathematical education (e.g., Stapel, Hunnius, Bekkering, & Lindemann, 2015).

[5] In non-human primates, the activity of number-sensitive neurons, which are located in the lateral intraparietal sulcus (LIP), changes in proportion to N (Roitman et al., 2007).

responded faster to small numbers [0-4] with lower manual button responses and faster to larger numbers [5-9] with upper button responses (Ito & Hatta, 2004; Hartmann, Gashaj, Stahnke, & Mast, 2014). In the original horizontal paradigm, this effect of numerical magnitude on response times was found to be independent of the hand performing the response, but dependent on the spatial location of the response keys on a left-to-right axis (Experiment 6; Dehaene et al., 1993).[6] Thus, the underlying mechanism seems not to depend on the hand performing the response, but, rather, on a more abstract organization of numerical magnitude in space (Schwarz & Keus, 2004).

Based on embodied cognition accounts (e.g., Wilson, 2002), many researchers suggested that the vertical (as well as horizontal and possibly sagittal) directionality of spatial-numerical associations originates in repeated and consistent sensory-motor interactions between humans and their environment (e.g. Winter et al., 2015).[7] After all, both the enumeration and sorting of numerosities afford perception and movements that extend in space. Specifically, researchers who argue for an embodiment of cognition suggest that the mind enriches and complements internal mental structures like semantic concepts with such basic sensory-motor experiences, which in turn are associated with relations and restrictions regarding body and the physical world (e.g., Barsalou, 2008, 2010; Glenberg & Gallese, 2012; Lakoff & Johnson, 1999). In line with this hypothesis, even abstract knowledge of numbers presumably relies on modally or multimodally *grounded* features of sensory-motor human-environment interactions (cf. Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). Regarding the mental number line, the association between numbers and spatial verticality hence might reflect the objective organization of the physical world according to gravity (a *tropic* or *grounded* representational feature; Myachykov, Scheepers, Fischer, & Kessler, 2014; Fischer, 2012). By contrast, numerical association to spatial horizontality supposedly reflects culture-specific experience like reading direction (an *embodied* representational feature; Myachykov et al., 2014). Confirming the latter claim, a SNARC experiments with native speakers who read and write words and numbers from right to left (e.g., native Arabic-speakers) showed reversed spatial-numerical associations. More precisely, Arabic-speaking Palestinians responded faster to small numbers with response buttons located to the right and vice versa for larger numbers (Shaki, Fischer, & Petrusic, 2009; see also

[6] Please note that a study by Wood, Nuerk, and Willmes (2006) failed to replicate the described primacy of space- over hand-based associations in the SNARC paradigm. Moreover, a study by Wiemers, Bekkering, and Lindemann (2017) gives evidence for a primacy of hand-based associations over space-based number mappings in the vertical dimension. By contrast, an experiment by Brozzoli and colleagues (Brozzoli, Ishihara, Göbel, Salemme, Rossetti, & Farnè, 2008) found evidence for both space- and body-based associations, but a preference for spatial-numerical associations in case of competition. Therefore, more research is needed to settle this dispute.

[7] In total, three orientations of the mental number line are postulated in the literature: horizontal (width), vertical (height), and sagittal (depth) (Winter et al., 2015). Although originally not specified (Restle, 1970), the horizontal orientation has been predominant in numerical cognition research (Winter et al., 2015).

Shaki & Fischer, 2008 for a reduced SNARC effect of bilingual Hebrew-Russian readers after being primed with Hebrew script).[8]

As *tropic* (or grounded) features of cognitive representations reflect the most invariant and stable features of our physical environment, the vertical version of the mental number line should be more stable than its culturally acquired horizontal sibling (Myachykov et al., 2014). Empirical evidence supports this notion, as Winter and Matlock (2013) found stronger effects of vertical spatial manipulations on numerical cognition than of horizontal spatial manipulations. In a recent study, Shaki and Fischer (2018) even challenged the notion of an inherent association of numbers with horizontal space (without prior activation of space or magnitude features) in two Experiments. However, their results indicated a purely conceptual link of numbers and vertical space (i.e., without spatial task affordances or even explicit number processing). Nonetheless, the vertically oriented mental number line has so far gotten less attention in numerical cognition research than the horizontally oriented one (Winter et al., 2015).

1.2 Operating numerical magnitude

1.2.1 Behavioral evidence for spatial-numerical associations

Due to its grounding in space, numerical cognition affects spatial codes and vice versa. In line with this hypothesis, several studies showed correspondence effects of small vs. large numerical magnitude with both active movements (e.g. finger pointing, Fischer, 2003; e.g., finger movement, Sixtus, Lindemann, & Fischer, 2018a; e.g., hand movements, Song & Nakayama, 2008) and passive motion detection (e.g., Hartmann Grabherr, & Mast, 2012, Experiment 3) to the left vs. right. In the study by Song and Nakayama (2008), participants indicated whether a given number was larger or smaller than *5* by touching a square to their left (for smaller numbers), to their right (for larger numbers), or in front of them (for number 5). Results demonstrated distance effects for the movement trajectories (and response times) in correspondence with the difference to 5: Direct lines lead to the left vs. right square for numbers 1 vs. 9, while trajectories in response to the other numbers were curved to the central square. Conversely, a large body of research showed that spatial codes involved in dynamic body movements (head-turning; body turns) on an up-down (or left-to-right) axis (Hartmann et al., 2012; Loetscher, Schwarz, Schubiger, & Brugger, 2008; Shaki & Fischer, 2014) influence random number generation (RNG; Evans, 1978). For instance, participants called out freely generated numbers between 1 and 30 while rhythmically (i.e., the beat of an electronic metronome) moving their head up and down in one, to left and right in another, and not at all in a third block.

[8] Nonetheless, recent studies indicated a culture-independent basis of numerical associations to horizontal directionality. Thus, one study showed that small numerosities shifted the visual attention of eight- to nine-month-old children to the left, larger ones to the right. Since shape size did not show a similar effect, this effect was interpreted as number-specific (Bulf, de Hevia, & Macchi Cassia, 2016).

Results revealed that participants generated larger numbers when they had their head tilted up compared to down (and less so when turned right compared to left; Winter & Matlock, 2013). Other studies extended this influence of embodied spatial codes to numerical trivia estimation (Eerland, Guadalupe, & Zwaan, 2011) as well as to the passive experiencing of whole body motion (e.g., via chair in vertical and horizontal space, Hartmann et al., 2012; see also Lugli, Baroni, Anelli, Borghi,& Nicoletti, 2013 for the influence of perceived elevator motion).

Beyond embodied and proprioceptive mediations between number and space, several authors showed that numerical cognition influenced tactile (e.g. Brozzoli, Ishihara, Göbel, Salemme, Rossetti, & Farnè, 2008) and haptic perception (e.g. Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010) and, vice versa, that tactile stimulation influenced event counting (e.g. Sixtus, Lindemann, & Fischer, 2018b). In two experiments by Brozzoli and colleagues (2008), participants performed better in a signal detection task if the number *1* relative to the number *5* preceded the tactile stimulation of the leftmost finger on their left hand. Interestingly, the leftmost finger changed in-between experiments: In the palm-down version (Experiment 1), the little finger was the leftmost finger; in the palm-up version (Experiment 2), it was the thumb. Consequently, the effect of numbers on tactile perception seems to depended on the representation of space rather than specific fingers - even though there was an additional, but weaker hand- associated effect as well.

Finally, past research has demonstrated effects of numerical magnitude and/or quantity on visuospatial attention (attentional SNARC effects, originally shown by Fischer Castel, Dodd, & Pratt, 2003; replicated by Dodd, van der Stigchel, Leghari, Fung, & Kingstone, 2008; Nicholls, Loftus, & Gevers, 2008; see also Masson & Pesenti, 2014)[9]. In a study Pecher and Boot (2011), participants detected a target presented at the bottom of a screen faster after having read pieces of information contextualizing a number as a small quantity (e.g. *The man had two books in his bookcase*) compared to information contextualizing it as a large quantity (e.g. *The man read two books a day*). The opposite pattern of results was found for targets presented at the top of the screen. Moreover, observational research indicated that upward eye movements preceded larger number generation whereas downward eye movements preceded smaller number generation (Loetscher, Bockisch, Nicholls, & Brugger, 2010). Complementing these findings (e.g. Hubbard, Piazza, Pinel, & Dehaene, 2005; Ranzini, Dehaene, Piazza, & Hubbard, 2009), neuropsychological research inspired speculations on an accentuated role of the visual modality for numerical cognition, which I will discuss below. However, there has been only very limited behavioral research on the effects of visuospatial manipulations on number processing (e.g. Grade, Lefèvre, & Pesenti, 2013), which stresses the relevance of

[9] Please note that there is a number of authors that had problems with replicating (e.g., Bonato, Priftis, Marenzi, & Zorzi, 2009; Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006) or failed to replicate the attentional SNARC effect (e.g., Zanolie & Pecher, 2014; for a discussion, see Fischer & Knops, 2014). Thus, more research is needed to settle this dispute.

the present work's agenda.

Taken together, the aforementioned behavioral experiments have demonstrated that the activation of spatial codes in the vertical (and horizontal) dimension via motoric action or sensory perception affects parallel or succeeding numerical cognition operations and vice versa. Considering common underlying mechanisms, determining locations in space attentionally seems to be involved in the described operations along the vertically (and/or horizontally) oriented mental number line. Specifically, the aforementioned experiments can be clustered into three manifestations of plurimodal attention orienting behavior, namely vision (Grade et al., 2013), touch (Brozzoli et al., 2008; and/or haptic, Cattaneo et al., 2010), or proprioception (e.g., Hartmann et al., 2012; and/or motoric, e.g., Winter & Matlock, 2013).[10] In line with this hypothesis, some authors have speculated that visuospatial attention in particular might be involved each time numerical magnitude is accessed (Hubbard et al., 2005; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009a; Ranzini et al., 2009). Indeed, Knops and colleagues (2009a) found similar brain activation patterns for eye movement and mental arithmetic operations, while others associated smaller-larger comparisons and addition with dynamic attention shifts (e.g. Knops, Viarouge, & Dehaene, 2009b) and/or analogue eye movements (Hartmann, Mast, & Fischer, 2016) on a mental number map. Therefore, visuospatial attention orienting seems to plays an accentuated role in processing magnitude along the mental number lines. However, as there are several indications of spatial-numerical association effects in blind people, i.e. in the explicit absence of visuospatial attention, visuospatial attention's involvement in numerical cognition seems to be replaceable (Cattaneo, Fantino, Silvanto, Tinti, & Vecchi, 2011; Cattaneo et al., 2010). Moreover, the breadth of effects speaks for a system based on multi- and/or cross-modal attention orienting rather than visual attention alone.

1.2.2 Functional equivalence of numerical magnitude operations and processing within peripersonal space

The present work proposes that the representations of space within reaching distance close to the body, which is often referred to as *peripersonal space* or *near space* (e.g. Holmes & Spence, 2004), link spatial codes to numerical magnitude via plurimodal spatial attention orienting. Indeed, some authors (Chen, Zhou, & Yeh, 2015; Longo & Lourenco, 2010) have already pointed out that operating numerical magnitude might share functional properties with this "action space" around us (Walsh, 2013). For instance, the study by Longo & Lourenco (2010) showed a common rightward bias of attention in perceptual and numerical space: Participants both overestimated the numerical midpoint between pairs of number and shifted the midpoint of physical lines to the right, when the stimuli were presented outside rather than within their

[10] Please note that in this context, the term *attention* is employed to describe processes "that give rise to a temporary change (often enhancement) in signal processing" (Spence, 2010).

peripersonal space. In line with these results, the present thesis proposes an extension of the shared functional features to the processing features of peripersonal space that subserve action and perception. In this section, let me first introduce peripersonal space definition and research in more detail. Then, I will trace back the suggested functional link between numerical magnitude operations and processing within peripersonal space to their shared origins in terms of *A Theory of Magnitude* (*ATOM*; Walsh, 2003, 2013). Finally, I will elaborate on the role of plurimodal spatial attention-orienting for processing within peripersonal space in the context of the former's suggested involvement in numerical magnitude operations.

Peripersonal space representation is defined as part of the neural body representation, because it encompasses the sphere surrounding the body in which physical interactions with the environment regularly occur (e.g. Pellencin, Paladino, Herbelin, & Serino, 2018; see Fig. 2). In line with this definition, humans were shown to respond faster and with more motoric precision to visuotactile stimuli presented within the interface between body and environment than when the same stimuli are presented far from the body (termed *extrapersonal space*; e.g. Sambo & Foster, 2009; Spence, Pavani, Maravita, & Holmes, 2004). Further elaborating on this finding, neuropsychological (e.g. di Pellegrino, Làdavas, & Farné, 1997; di Pellegrino & Làdavas, 2015) and neuroimaging (cf. Blanke, Slater, & Serino, 2015; Cléry, Guipponi, Wardak, & Ben Hamed, 2015) research traced these processing benefits back to a more fine-grained multisensory and motor integration of body-relevant cues within peripersonal space relative to outside (e.g. Pellencin et al., 2018). However, it is important to note that not egocentric distance to the body as a whole, but proximity to specific body parts like hand and face were shown to be decisive as they reflect one's actual reaching distance (e.g. Valdés-Conroy, Sebastián, Hinojosa, Román, & Santaniello, 2014; see Fig. 2). Thus, several authors stress the privileged representation of head and hands/arms due to their role in shaping and acting on one's visual and reaching field (e.g., Cléry et al., 2015; Holmes & Spence, 2004; see the right half of Fig. 2). This close association of peripersonal space processing to action has an equivalent in numerical cognition theory and research - but naturally in terms of number-action links (Walsh, 2013).

A Theory of Magnitude (ATOM) links spatial-numerical associations to action based on notions of embodied cognition (Wilson, 2002). In line with this view, even abstract semantic concepts like numbers are grounded in the low-level perceptual and motor codes associated with their acquisition (Barsalou, 2008; Fischer & Zwaan, 2008; Glenberg & Kaschak, 2002). Therefore, a functional link between peripersonal space and numerical magnitude representations might be traced back to the origins of numerical magnitude processing in the manipulation of objects via reaching and grasping (Walsh, 2013). After all, peripersonal space processing is essential for the sensory guidance of motor behavior for the purpose of interaction with objects and humans alike (di Pellegrino & Làdavas, 2015). In this context, A Theory of Magnitude outlines a *Generalized Magnitude System* (*GMS*) for quantity and other *prothetic* dimensions like space, and time, i.e. dimensions that can be understood and experienced along a less-more continuum (cf. Stevens, 1957).[11] This generalized system supposedly encodes all magnitude information in the external world according to a common sensory-motoric metric in shared codes rather than in separate and specialized structures (Walsh, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001). Based on an assumed functional equivalence of generalized (rather than only numerical) magnitude operations and peripersonal space processing, Walsh (2013) predicted that the distance between actor and object should affect magnitude processing in general and numerical magnitude operations in particular (see Fig. 2).[12] However, the functional equivalence of number and peripersonal space processing need not be restricted to shared spatial limitation (like in Chen et al., 2015; Walsh, 2013), but might extend to other functional features relevant for action, in particular spatial attention orienting.

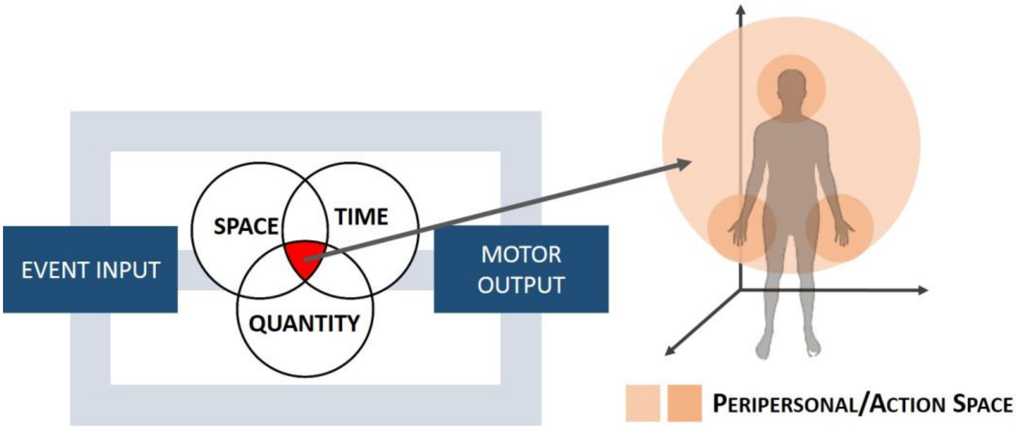

Figure 2. A Theory of Magnitude (Walsh, 2003, 2013) suggested that the Generalized Magnitude System originate in the necessity to compute magnitudes for action. Therefore, the figure shows *action space* as a feature shared between different magnitude dimensions such as space, quantity, and time. Please note that the *peripersonal* space representation (i.e., space within reaching distance) surrounding one's body is highlighted in light orange. Head- and hand-centered peripersonal space are stressed due to their accentuated role in body-environment interactions.

With regard to the initial argument, plurisensory attention orienting (and its visual manifestation in particular) plays a significant role within the "multisensory-motor representation of the body in space" (Pellencin et al., 2018, p. 164) that peripersonal space essentially is. Thus, vision is one of the central modalities in mentally constructing and attentionally orienting oneself within peripersonal space (e.g. van der Stoep, Serino, Farnè, Di Luca, & Spence, 2016). In line with this view, past research showed that

[11] Further research extended the dimensions of the Generalized Magnitude System to magnitudes in terms of luminance (e.g. Cohen Kadosh, Cohen Kadosh, & Henik, 2008) loudness (Hartmann & Mast, 2017), and pitch height (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006).

[12] Please note that the generalized aspect of this deduction goes beyond the scope of the upcoming Empirical Part. Therefore, I will focus on the implications for numerical cognition for the remainder of the Introduction.

congruent visual and bodily somatosensory stimulation can flexibly shape peripersonal space representation both in body (e.g. Lenggenhager, Metzinger, Blanke, 2007) and part-body (e.g. rubber hand illusion, Botvinick & Cohen, 1998) illusions. Moreover, participants performed better in a visuospatial detection task (Li, Watter, & Sun, 2011) and benefited more from cueing (Losier & Klein, 2004) when objects appeared within peripersonal space relative to extrapersonal space. In consequence, both empirical findings that suggest strong involvement of visuospatial attention orienting in numerical cognition (e.g., Knops et al., 2009b), and those that indicate a mediation via other modalities (Cattaneo et al., 2011; Cattaneo et al., 2010) are compatible with the processing features within peripersonal space.

In sum, the present thesis brings together numerical magnitude operations and peripersonal space processing when it proposes that their functional equivalence is not restricted to their spatial limitation (see Chen et al., 2015; Walsh, 2013), but extends to plurimodal spatial attention orienting. This novel proposition is based on the shared origins of both types of representations in perception and action. Moreover, it reflects both the plurisensory processing principles of action space (Pellencin et al., 2018) and the pluri- and crossmodal nature of the spatial mechanism that presumably underlies the numerical cognition studies presented in the last section (visuospatial attention orienting: e.g., Grade et al., 2013, tactile attention orienting: e.g., Brozzoli et al., 2008; proprioception: e.g., Hartmann et al., 2012). Finally, the extended functional equivalence assumption has implications for numerical cognition research that I will outline in the next section.

1.2.3 Implications of functional equivalence of numerical magnitude operations and peripersonal space

Several implications follow from the suggested functional equivalence between numerical magnitude operations and peripersonal space processing. The first implication is that changes within action space that cue spatial attention orienting responses should extend to numerical magnitude operations. Among the aforementioned numerical cognition studies, both the studies relying on visual (e.g., Grade et al., 2013) and tactile stimulation (e.g., Sixtus et al., 2018b) fall into this category. In the opposite direction, the study by Brozzoli and colleagues (2008) demonstrated visually perceived numbers had cross-modal effects on tactile perception within participants' near space. A second implication is that changes of peripersonal space processing that occur due to movements and posture should extend to number processing. In support of this hypothesis, Winter and Matlock (2013) showed vertical and horizontal head movement effects in a Random Number Generation task. Moreover, the same should be true for permanent changes of near space representation, for example in consequence of brain lesions. Indeed, hemispatial neglect patients were not able to call out the correct midpoint of numerical intervals (e.g., calling out 5 as midpoint between 2 and 6; Zorzi, Priftis, & Umiltà, 2002).

Another implication, which circumscribes the agenda of the present thesis, is built on the effects of others on one's peripersonal space representation. More precisely, merely observing changes of (or stimuli within) others' peripersonal space should extend to one's own number processing. Past research on near space representation showed that the presence of others could either increase or reduce the extent of one's peripersonal space representation (Pellencin et al., 2018). For instance, a recent study by Teramoto (2018) demonstrated that target detection times did not only decrease when a disk approached the participants' own hand, but also when it approached a partner's hand in her/his peripersonal space. Other behavioral (e.g. Costantini, Committeri, & Sinigaglia, 2011; Costantini, Ambrosini, Cardellicchio, & Sinigaglia, 2013; Fini, Brass, & Committeri, 2015; Maister, Cardini, Zamariola, Serino, & Tsakiris, 2015) and physiological studies (e.g. Brozzoli, Gentile, Bergouignan, & Ehrsson, 2013) indicated that observing others results in a remapping of the observer into the observed person's peripersonal space. Additional research indicated that such remapping of peripersonal from the observed person's reference frame occurs naturally and need not be instructed (Becchio, Del Giudice, Dal Monte, Latini-Corazzini, & Pia, 2011; Samson, Apperly, Braithwaite, Andrews, & Bodley Scott, 2010). Thus, current research indicates that peripersonal space representations are shared between oneself and others based on sensory-motor simulation mechanisms (e.g. Ishida, Nakajima, Inase, & Murata, 2010; Teramoto, 2018). Nonetheless, this social implication of the functional equivalence assumption has not yet been addressed in numerical cognition research.

The present work aimed at investigating if observing changes in someone else's peripersonal space representation extended to one's own numerical magnitude operations (Experimental Series B). An immediate way of testing this hypothesis is the observation of others' head orientation behavior during or before number processing. The reason for that is that someone's head orientation is a proxy for her/his visual field, which in turn determines her/his head-centered visual peripersonal space representation (e.g., Làdavas, Zeloni, & Farnè, 1998b). Moreover, not only events within one's own peripersonal space were shown to affect one's visuospatial attention orienting (in contrast to events in one's extrapersonal space; e.g. Losier & Klein, 2004). Social cueing research demonstrated that others' static directional head postures triggered attention shifts in observers (e.g., Langton & Bruce, 1999; see Fig. 3) – as did others' centrally presented spatial gaze, head, body and gesture information (for a review, see Frischen et al., 2007). At this point, research on implications peripersonal space representation and social cueing intertwine. Therefore, I will review the literature on social cueing effects of head orientation with special consideration of vertical cues in the next chapter. Nonetheless, the critical question that will be addressed in this work is if such a socially induced attention shift extends to the observer's number operations as well.

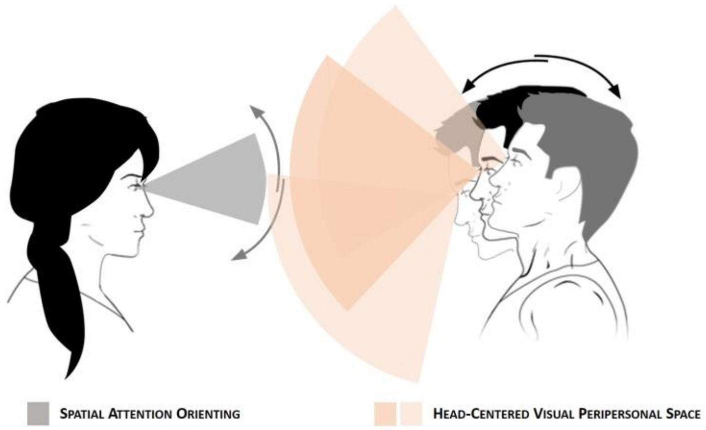

Figure 3. The figure visualizes an observer's attention orienting shift in correspondence with changes in an observed person's head-centered peripersonal space representation (i.e., her/his visual field).

In sum, the assumption that numerical cognition operations are functionally equivalent to peripersonal space processing has several implications. Firstly, events within one's near space were shown to trigger a spatial attention orienting response (Teramoto, 2018) and to affect one's numerical magnitude operations (Sixtus et al., 2018b). Secondly, changes of one's peripersonal space representation were shown to affect both one's attention orienting in perceptual and numerical space (e.g., Zorzi et al., 2002). Thirdly, observing others was shown to affect the observer's peripersonal space processing (e.g., Costantini et al., 2011). Please note that social cueing research is interested in spatial attention shifts in response to observing others' behavior or posture (here: head orientation; e.g., Langton, 2000). In this context, the present research brought together numerical cognition, peripersonal space processing, and social cueing research when it investigated if this effect also extended to the observer's numerical magnitude operations. For this purpose, the relevant social cueing literature will be reviewed in the next section.

1.3 Attention orienting in response to others' spatial behavior

1.3.1 Effects of observing other's bodily cues on spatial attention

Viewing centrally presented social cues like averted gaze (gaze following), turned heads, posed bodies, pointed fingers, or faces that look at us (direct gaze effect) triggers attention orienting in the observer (Driver, Davis, Ricciardelli, Kidd, Maxwell, & Baron-Cohen, 1999; Friesen & Kingstone, 1998; Friesen, Moore, & Kingstone, 2005; Langton, 2000; Langton & Bruce, 1999, 2000). For instance, a myriad of studies demonstrated that perceiving another person's gaze direction results in corresponding reflexive attention shifts and response time advantages for gazed-at locations - even if it is more likely that the target appeared not in the cued location (Driver et al., 1999; Friesen & Kingstone, 1998; for a review, see Frischen et al., 2007).[13] Gaze following behavior was demonstrated even in young infants (10 months of age or older; e.g. Brooks & Melzoff, 2005) and non-human primates like rhesus macaques (Emery, Lorincz, Perrett, Oram, & Baker, 1997; Rosati, Arre, Platt, & Santos, 2016), which renders it an evolutionarily deep-wired predisposition (Emery, 2000). By comparison, only a small number of studies investigated the effects of head orientation (e.g., Langton, 2000) or striking misalignments of gaze and head direction (e.g. Hietanen, 2002; Pomianowska, Germeys, Verfaillie, & Newell, 2012) on how observers distribute attention in space.

Empirically, social cueing research used variants of Posner's famous spatial cueing task (Posner, Snyder, & Davidson, 1980) and similar paradigms (e.g. Langton, 2000; Pomianowska et al., 2012; van der Wel, Welsh, Böckler, 2018; Zeligman & Zivotovsky, 2018) to investigate the effects of an observed person's nonverbal cues (gaze, head, body, gestures) on the observer's attention orienting. For instance, Langton (2000; Langton & Bruce, 1999) investigated the influence of additional head orientation on such gaze cueing effect. Specifically, Langton (2000) demonstrated response time advantages for targets that appeared in vertical locations cued by the aligned gaze and head direction of a centrally presented person. However, if directional gaze and head information were in opposition to each other, this attention orienting was nullified both in vertical (Langton, 2000) and horizontal dimensions (Langton & Bruce, 1999). These results are especially interesting for the present work as observed head orientation shapes the visual field of the observed person and indicates which parts of her/his peripersonal space representation are at the focus of her/his attention (e.g., Làdavas et al., 1998b). Nonetheless, there has been only a small number of social cueing studies interested in the effects of head orientation on an observer's visuospatial attention orienting in more detail.

1.3.2 Attention orienting in response to head orientation

Investigating more complex gaze-head misalignments, Hietanen (1999) revealed integrative effects in the horizontal dimension. In one study, participants showed response time advantages for targets that appeared in locations opposite to those cued by misaligned head orientations. Please note that in the pictures used by Hietanen (1999), gaze was directed straight at the observer, i.e. slightly to the location opposite to that cued by the head (see Fig. 4). Thus, participants seemed to *overshoot* due to the misaligned head context of the direct gaze (see Fig. 4). Moreover, the same study indicated that aligned gaze-head constellations to the left or right of the observer did not result in

[13] Please note that in the present thesis, "cueing" refers to general alerting benefits of social cues irrespective of their validity. This means that if not explicitly indicated otherwise, all studies outlined in this section and the Empirical Part used social stimuli that did not cue the correct location in a majority (or minority) of trials. In consequence, the social cues employed in the present work did not objectively reduce information, but primed cognitive operations (Sudevan & Taylor, 1987).

attention orienting responses (Hietanen, 1999). In later studies, these integrative effects were extended to misaligned head-body postures (Hietanen, 2002; for an overview, see Frischen et al., 2007).

Figure 4. Example pictures of a model with his head turned to the left (left), from a frontal view (center), and with the head turned to the right (right) analogue to those used in the experiments by Hietanen (1999). Please note that gaze is directed at the observer irrespective of head orientation. The direction of the arrows above the pictures to the left and right indicate the respective directions to which observers' spatial attention shifts *overshooted* in response to the misaligned head context of the direct gaze (Hietanen, 1999).

To explain attention orienting in response to another's misaligned gaze, head and/or body postures, several models postulated direction-detection mechanisms in the brain (e.g. Baron-Cohen, 1995; Perrett, Hietanen, Oram, Benson, & Rolls, 1992; for a review, see Langton, Watt, & Bruce, 2000). For instance, Perrett and colleagues' (1992) suggested a detection system that processes information from eye-, head-, and body-directions hierarchically; in case of conflicting information, gaze overrides both head and body information and head overrides body information (see Fig. 5). Refining the model by Perrett and colleagues (1992), Hietanen (2002) outlined a more integrative multi-step process, in which spatial information from all three information carriers is referenced to each other to select one holistic attention orienting response (Pomianowska et al., 2012). Interestingly, the predictions of Perrett's (1992) and Hietanen's (2002) models differ only incidentally from each other as Hietanen (2002) assumes a hierarchical processing mode with gaze as most diagnostic feature (henceforth, both accounts are subsumed in the label *gaze-priority accounts*). In stark contrast, Langton's (2000) integrative direction-detection mechanism (henceforth labelled additive-*contributions account*) processes the contributions of gaze, head, and body in parallel. Thus, he assumed independent and additive contributions from all three references that result in systematically deviating predictions relative to Hietanen (2002) and Perrett and colleagues (1992). The question if the head is an effector on a par with gaze is of significance for the present work. After all, peripersonal space processing in the vertical (relative to the horizontal) dimension should be affected more strongly by changes in head orientation than gaze direction due to the arrangement of the eyes and the shape of the eye sockets. Thus, it is anatomically impossible to look down to what's below one's chin with the head tilted down, or up to what's above one's eyebrows with the head tilted down (see Fig. 3). In line with these considerations, a recent study indicated an asymmetry between the vertical and horizontal dimension in natural gaze-head alignment behavior (Fang, Nakashima, Matsumiya, Kuriki, & Shioiri, 2015).

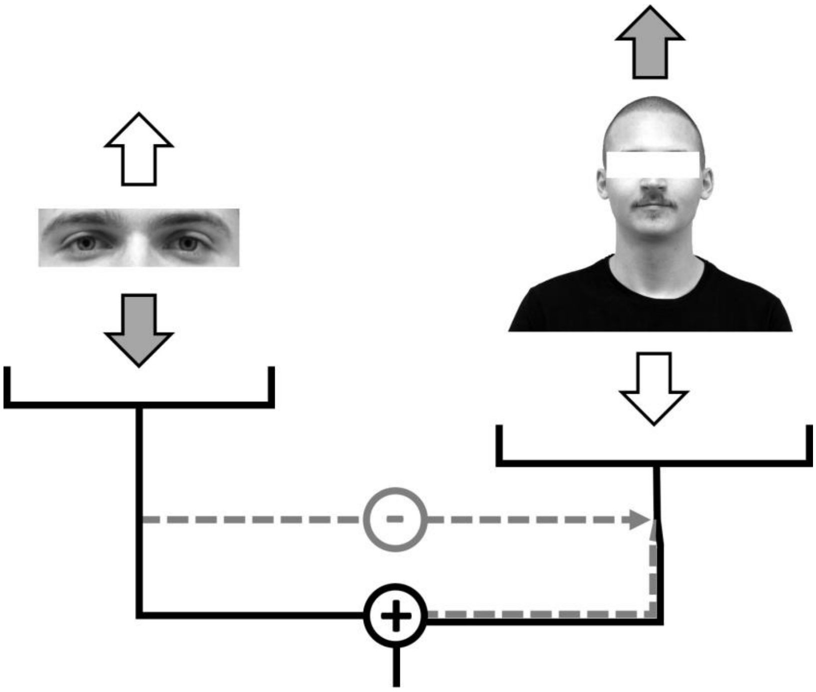

Figure 5. The figure shows details of the outlined direction-detection mechanisms concerning head-gaze alignment. The arrows above and below the pictures indicate the direction of gaze (left) and head (right) movement. The black lines outline the *additive-contributions* direction-detection mechanism suggested by Langton (2000). According to this account, the contributions of gaze and head are processed in parallel and integrated additively into one holistic spatial attention orienting response. By contrast, *gaze-priority* accounts (Hietanen, 2002; Perrett et al., 1992) assume a hierarchical processing mode with gaze as most diagnostic feature (for a review, see Langton et al., 2000). Consequently, gaze direction overrides head information in cases of conflict (Perrett et al., 1992) or is reinterpreted in the context of conflicting head information (Hietanen, 2002). In both cases, the spatial attention-orienting response should be computed in terms of the gray dashed line. The results differ systematically from those predicted by the additive-contributions account (see Pomianowska et al., 2012). Please note that cases of conflicting gaze and head directions are indicated by the colors of the arrows. Directional conflicts can be both absolute (i.e., head tilted up and gaze directed down; Langton, 2000) and relative (i.e., head tilted up and gaze directed at the camera; see Empirical Part of the present work).

In recent years, social cueing research has shown renewed interest in the interactive attention orienting effects of observed gaze direction, head orientation and body posture in the horizontal dimension. For instance, Moors and colleagues (Moors, Germeys, Pomianowska, and Verfaillie, 2015) as well as Pomianowska and colleagues (2012) investigated the effects of static head-body misalignments in the horizontal dimension. Results are in line with Perrett's (1992) and Hietanen's (2002) hierarchical rather than Langton's (2000) integrative direction processing mode (similar to the overshoot effects; Hietanen, 1999, 2002). Considering the agenda of the present thesis, however, vertical head movement or posture is the more promising stimulus material in the context of numerical cognition tasks. After all, embodied cognition theorizing predicted that vertical space was a more stable feature of number representation than horizontal space (Myachykov et al., 2014). Therefore, Experiment 3 (Experimental Series A) tested the effects of misaligned gaze-head postures on observers' spatial attention orienting in the vertical dimension.

Furthermore, classical gaze cueing research employed both static and dynamic setups. Static setups consist of a centrally presented picture of a person with averted gaze. By contrast, dynamic setups show a picture of a person with straight gaze that is replaced by a picture of the same person with averted gaze after a few hundred milliseconds. Empirical evidence indicates that dynamic cueing stimuli produce stronger effects than static stimuli (Frischen et al., 2007). In this context, it is important to note that more recent authors that investigated gaze-head and head-body misalignments suggested that motion perception implied in the respective postures were responsible for the effects (e.g. Moors et al., 2015; Pomianowska et al., 2012). Nonetheless, all misalignment studies have used static stimuli only (e.g. Hietanen, 1999, 2002; Pomianowska et al., 2012; Moors et al., 2015; Langton, 2000), which is why we can only speculate about how an additional movement might affect the implied motion perceptions (Moors et al., 2015). To address this additional gap in the head cueing literature, Experiment 1 and 2 of (Experimental Series A) employed dynamic instead of static vertical head orientation stimuli.

In sum, other's bodily cues (gaze, head, and/or body) were shown to trigger spatial attention shifts in an observer (for a review, see Frischen et al., 2007). This finding is in line with research on social modulations of one's peripersonal space (cf. di Pellegrino & Làdavas, 2015). Relative to gaze cueing research (e.g., Driver et al., 1999), however, there has been only limited research on the effect of head orientation on an observer's spatial attention orienting (Langton, 2000). Moreover, several accounts make competing predictions on how gaze and head information interact when viewing misaligned gaze-head postures (e.g., Hietanen, 2002; Langton, 2000). Finally, there has been neither research on misaligned gaze-head constellations in the vertical dimension, nor on movements between aligned and misaligned postures. These gaps in social cueing research were relevant for the agenda of the present thesis for two reasons: (1) Head orientation is a proxy for head-centered peripersonal space (cf. di Pellegrino & Làdavas, 2015). (2) Numerical associations to vertical space were predicted to be more stable than those to horizontal space (Myachykov et al., 2014). Therefore, the first three Experiments of the present thesis tested the effects of down- and up-tilted head pictures with gaze directed at the camera on observers' spatial attention orienting (Experimental Series A). This preparatory work was necessary to understand the spatial attention orienting effects triggered by the stimulus material employed in the numerical cognition Experiments 4 to 6 (Experimental Series B). After all, the agenda of the present work was to investigate if observing changes in someone else's head-centered peripersonal space representation extended to one's own numerical magnitude operations.

1.4 The present research: Social cueing of numerical magnitude

1.4.1 Significance and limitations of past research

Gaze cueing of numerical cognition

Paving the way for bringing together numerical and social cognition, Grade and colleagues (2013) suggested that observing another person's gaze movements in close-up view could be sufficient for an effect on numerical cognition. Specifically, participants were instructed to generate numbers between 1 and 10 after having viewed a pair of eyes looking to the left or right (Experiment 1), or to the bottom or top (Experiment 2). In control trials, only the color of the eyes was changed. Results showed that participants generated smaller numbers when the eyes looked to the left or downwards relative to the control conditions. Based on gaze cueing research (e.g. Driver et al., 1999; Friesen et al., 2005), the authors concluded that the spatial cue inherent to the averted eyes not only shifted attention in outer *perceptual space* but also on the mental number line in inner *mental space*.

In spite of its merits, Grade and colleagues' (2013) eye movement manipulation has several limitations. Firstly, following a pair of eyes in close-up view shifting up vs. down (to the left vs. right) comes closer to a visuospatial response to an event in one's own peripersonal space than to a response to another person's direction of attention within his/her own peripersonal space. Secondly, social cueing paradigms typically used portrait-like photographs of faces instead of pictures of eyes as stimuli (Frischen et al., 2007), even if they investigated the influence of gaze cues alone (e.g., Driver et al., 1999). One reason for this more holistic approach to gaze cueing is the interest of social cueing research in interactions between gaze, head, and body information in triggering orienting responses in observers (Frischen et al., 2007; Hietanen, 1999; Langton & Bruce, 2000; Langton et al., 2000). Therefore, I argue that portrait-like head stimuli are better suited for testing whether observing others' head-centered peripersonal space orienting shifts the observer's attention in both perceptual (Experimental Series A) and numerical space (Experimental Series B).

Methodological and interpretational criticism of numerical cognition research

Critics of numerical cognition research argue that the majority of behavioral studies in this field confounded spatial stimuli and non-spatial responses or vice versa (e.g., Fischer & Shaki, 2016; Shaki & Fischer, 2018). In line with this view, response code effects like the SNARC effects could result from polarity correspondence between positive (large) and negative (small) numerical polarity on the one hand and positive (top) and negative (bottom) spatial polarity on the other hand (Proctor & Cho, 2006; Roettger & Domahs, 2015). This alternative explanation provides a more parsimonious explanation for spatial-numerical associations than the notion of a mental number line. Nonetheless, polarity correspondence cannot account for results in Random Number Generation experiments (like Winter & Matlock, 2013; cf. Winter et al., 2015). Moreover, in order to refute such methods-based explanations, Fischer and Shaki (2016) developed a double classification task. In their study, participants performed a speeded go-nogo task with one response key only in two types of trials: (1) In half of the trials, a number (1, 2, 8, and 9) was presented; (2) in the other half, a cartoon image (duck or car) oriented to the left or right was presented. Participants had to press (or had to refrain from pressing) the key depending on a double response rule that combined numerical magnitude (*smaller vs. larger than 5*) and object orientation (*facing to the left vs. right*). In consequence, participants had to keep in mind one response rule combining instructions for both types of trials, which were counterbalanced across four blocks. Results showed that participants responded faster (in the go-trials) when the response rule combined either cartoon image orientation to the left and the judgment "smaller than 5", or cartoon image orientation to the right and the judgment "larger than 5". The opposite was true for the incongruent response rule combinations (i.e., either cartoon image orientation to the right and the judgment "smaller than 5", or cartoon image orientation to the left and the judgment "larger than 5"). Thus, a conceptual link between numbers and space is an explanation better suited for these results than polarity correspondence. Following this example, the present thesis took efforts to consider the methodological criticism of numerical cognition research outlined above in Experimental Series B. More precisely, Experiment 4 employed a Random Number Generation task (Evans, 1978), Experiment 5 a numerical estimation task and Experiment 6 a double dissociation task similar to that of Fischer and Shaki (2016).

1.4.2 Overview of the empirical part

The present work aimed at investigating (1) if observing changes in someone else's peripersonal space representation affected one's spatial attention orienting (Experimental Series A) and, crucially, (2) if such a socially cued spatial attention shift extended to one's own numerical magnitude operations (Experimental Series B). Thus, the agenda of the present thesis was twofold: Firstly, the present thesis hypothesized that changes in a person's head-centered peripersonal space due to his/her head movement and/or position affected an observer's attention orienting in accordance with the observed person's frame of reference (Experimental Series A). To disentangle if gaze or head was the effector in the head orientation stimuli, the present thesis used photographs of persons with gaze directed at the camera while their heads were tilted up or down (or not tilted; see Fig. 6). Specifically, Experiments 1 and 2 tested to which location attention was shifted in response to the observation of someone else's head movement from an aligned (head not tilted) to a misaligned gaze-head posture (head tilted up vs. down; Experiment 1) or vice versa (Experiment 2). Experiment 3 reduced the paradigm to the effects of static misaligned gaze-head postures (head tilted up vs. down) on observers' visuospatial attention.

Secondly, the effect of observed vertical head positions on spatial attention orienting was hypothesized to extend to corresponding smaller-larger operations with numerical magnitude (Experimental Series B). In contrast to Grade and colleagues' (2013) reduced gaze cueing stimuli, the present experiments used holistic vertical head postures indicating changes in the observed person's visual field (affecting her/his own PPS representation). Moreover, the present research took efforts to substantiate that the head-orientation effects on numerical cognition are the result of a conceptual link between numbers and space and not of spatial task demands (see Fischer & Shaki, 2016). Specifically, participants in Experiments 4 and 5 saw static head orientation stimuli until (but not while) they had to produce a random number between 1 and 9 or a numerical estimate (one- to multi-digit numbers) in response to a numerical trivia question. Experiment 6 employed a more indirect measurement task as participants could freely choose between two response keys when viewing the head orientation stimuli. Crucially, the employed response keys were associated to magnitude judgments (smaller vs. larger) via intermixed numerical magnitude trials. In sum, the present research systematically tested attention orienting in response to misaligned gaze-head postures in the vertical dimension and applied these stimuli to a variety of numerical task settings. In sum, the present thesis recruited social cueing research for the purpose of testing the social implication of assumed functional equivalence between processing within peripersonal space and numerical magnitude operations.

2 | Experimental Series A: Head cueing of spatial attention

Experimental series A sought to demonstrate that observing dynamic or static directional changes in a person's visual field (i.e., head-centered peripersonal space around the face; cf. di Pellegrino & Làdavas, 2015) due to his/her vertical head position affects the observer's spatial attention orienting (Experimental Series A). Specifically, portrait-like photographs from a frontal view with gaze directed at the camera but head tilted up vs. down (i.e. misaligned) vs. not tilted (i.e. aligned gaze-head posture) were used as social cueing stimuli (see Fig. 6). To simulate vertical head movements, one centrally presented picture of a head not tilted was replaced by that of the same person with head tilted up or down - or vice versa (Experiments 1-2). In all three experiments, participants saw tilted head pictures before and while they had to classify a vertically presented (above vs. below the picture) shape as circle or square (cf. Xu & Tanaka, 2015). Please note that the target appeared within the observed person's peripersonal space.

In Experiment 1, pictures with heads not tilted preceded pictures with tilted heads before the target appeared in addition. In Experiment 2, pictures with heads not tilted followed pictures with tilted heads before the target appeared in addition. In Experiment 3, participants viewed the tilted head pictures alone before the target appeared in addition (i.e., static head stimuli were employed). In line with the holistic additive-contributions account (Langton, 2000), target classification should be faster if direction of observed head orientation (shift) and location of target correspond than if they do not. Please remember that Langton (2000) predicted that directional head and gaze information are additively (rather than hierarchically) integrated into one holistic spatial attention-orienting response (see Fig. 5). In this view, head direction is the sole directional information within the misaligned gaze-head postures, which is why spatial attention-orienting should follow head orientation direction. Alternatively, if gaze-priority accounts (Hietanen, 2002; Perrett et al., 1992) hold true, target classification should be faster if direction of observed head orientation (shift) and location of target do not correspond than if they do. Please remember that both Hietanen (2002) and Perrett and colleagues (1992) predicted that gaze as most diagnostic feature of another person's actual spatial attention orienting overrides head information in cases of conflict. This gaze prioritizing computation process should result in an overshooting from relative gaze direction in the context of the tilted head postures to the location opposite of that indicated by head direction (see Fig. 5 and Fig. 6).

2.1 Experiment 1

Experiment 1 examined the hypothesis that observation of dynamic head shifts from a non-tilted to an up- or down-tilted position (i.e. in the vertical dimension) results in response time advantages for target-classifications in congruent relative to incongruent locations. In each trial, a photograph of a person with the head not tilted preceded that of the same person with the head tilted up or down immediately before the target appeared in addition. Thus, head orientation shifted from an aligned to a misaligned gaze-head posture. Please note that models in all three types of pictures looked directly at the camera (i.e. observer).

Social cueing accounts make opposite predictions regarding which locations are congruent and incongruent relative to the tilted head pictures. Gaze-priority accounts (Hietanen, 2002; Perrett et al., 1992) predict that gaze direction is dominant and automatically contextualized within its tilted head context. As a result, participants should follow the slightly upward directed gaze in the down-tilted head pictures and the slightly downward directed gaze in the up-tilted head pictures (see Fig. 6), which should result in response time advantages for locations opposite to head tilt direction. By contrast, an additive-contributions account (Langton, 2000) predicts no gaze cueing effect as the eyes contain no directional, but only ostensive information (e.g. Böckler, Knoblich, & Sebanz, 2011). Instead, his model expects participants to follow head direction, which should result in corresponding response time advantages for locations in line with vertical head orientation Employing dynamic misaligned gaze-head cues in the vertical dimension, Experiment 1 empirically tested the predictions of gaze-priority (Hietanen, 2002; Perrett et al., 1992) and additive-contributions (Langton, 2000) accounts against each other.

2.1.1 Methods

Participants

38 volunteers (28 female, 9 male, M = 28.03 years, range: 18-60; one data set was missing due to a computer crash) from the Würzburg area participated in the experiment. Participants received a financial compensation for study participation. Due to the absence of reliable a-priori knowledge on the expected effect size, we collected data of n = 38 participants. A sensitivity analysis showed that with this sample size, a medium-sized effect of $d_z \geq 0.47$ could be detected with a statistical power of $1-\beta = .80$ in a two-tailed paired-samples t-test with alpha-level = .05 (calculated with G*Power 3.1; Faul, Erdfelder, Lang, & Buchner, 2007).

Apparatus and stimuli

The experiment was run on Computers using Inquisit 5 software (Inquisit 5, 2016). The priming stimuli consisted of 54 portrait-like photographs (1158 x 1158 pixels) of 18 models (nine male, three pictures per person) taken from a set of photographs of 21 models (ten male, three pictures per person; overall 63 portrait-like photographs). Pictures were postprocessed to a white background color and shadows were removed. The color saturation was set to minimum (grey color). Contrast and brightness of the pictures were matched using Adobe Photoshop CS6. The photographs can be viewed in an Open Science Framework repository[14] (for an example picture triad, see Fig. 6). The models were between 18 and 65 years old. Each model wore a uniform black shirt and was shown from a front view with line of sight towards the camera. From the 54 pictures, one third (18 pictures) showed the model with the head tilted up (henceforth called *up-tilted heads*); a second third with the head tilted down (*down-tilted heads*). In the remaining pictures the head was not tilted (*non-tilted heads* as controls). For a quantitative measure of the head tilt, the distance between the line of the chin and the bottom of the picture was measured. The down-tilted heads had distances ranging between 0.21 and 0.67 cm (M = 0.53, SD = 0.11), the non-tilted heads ranged between 0.75 and 1.05 cm (M = 0.91, SD = 0.08), the up-tilted heads between 1.31 and 1.66 cm (M = 1.45, SD = 0.11).

Figure 6. Example picture of one model with his head tilted down (left), not tilted (middle) and tilted up (right) as presented in Experiments 1-6. Please note that gaze is directed at the observer in all three head pictures.

Procedure

Each trial started with a fixation cross that was replaced by the picture of a person with the head not tilted after 500 ms. After another 1,000 ms, the non-tilted head picture was replaced by a picture of the same person with the head tilted up or down. The target shape appeared on the screen in addition to the tilted head picture another 300 ms later. The target was either a circle or a square in blue color that was presented in a central location above or below the photograph (10% of the screen size below the top of the screen or above the bottom of the screen). Target and picture were displayed until response registration (see Fig. 7) or until 2,500 ms had elapsed. In the latter case, a message appeared for 2,000 ms telling the participant to respond faster. In case of an incorrect response, an error message appeared for 2,000 ms. The next trial was initiated after a variable inter-trial interval (500-1,000 ms in steps of 100 ms).

Participants were instructed to classify the shape of the target as fast as possible using the keys “F” and “J” on the keyboard (counterbalanced between participants). The

[14] Link: https://osf.io/rtkdp/?view_only=9bc2382dd85946fc8cd5f8a86d4a8125

experiment consisted of one practice block with eight trials and three experimental blocks with 72 trials each. All eight combinations of target (circle, square), target location (above, below the picture), and head orientation shifts (up, down) were shown nine times in each block. Two down-tilted and two-up-tilted head pictures of each person were shown per block. There were no repetitions of pictures of the same person in two consecutive trials. Apart from these restrictions, the two types of tilted-head picture combinations (non-followed by up-tilted vs. non- followed by down-tilted) were presented in random order across trials. Participants had a short rest period in between blocks with a reminder of the task instructions.

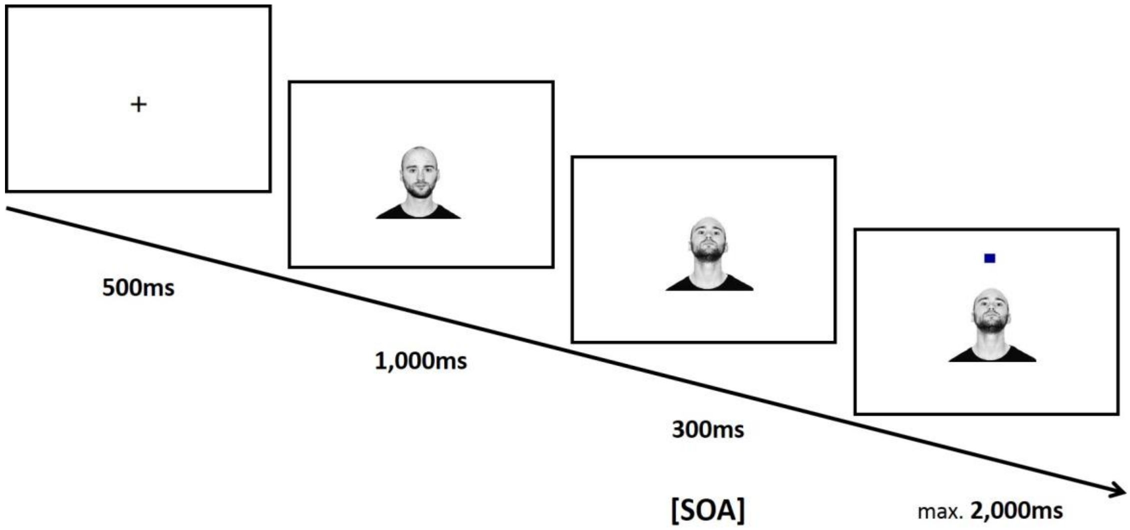

Figure 7. Sequence of events in a congruent trial of Experiment 1. Please note that in each trial, a non-tilted preceded a tilted head picture of the same person before the target appeared in addition. Participants were instructed to classify the blue target as circle or square using the keys “F” and “J” or vice versa (counterbalanced between participants).

Data Analysis

Mean response times (RTs) and error rates were computed for congruent trials (shift from non-tilted to down-tilted head with target below the photograph, shift from non-tilted to up-tilted head with target above the photograph) and incongruent trials (shift from non-tilted to down-tilted head with target above the photograph, shift from non-tilted to up-tilted head with target below the photograph). Trials with incorrect responses (7.9% of all trials) were removed from the RT analyses. Moreover, five participant were removed from the analysis due to his high percentage of incorrect trials (>20% of all trials incorrect). In addition, 2.9% of trials were removed due to individual Tukey thresholds (Tukey, 1977). The remaining mean RTs and mean error rates of congruent versus incongruent trials were submitted to two-tailed paired-samples t-tests.

2.1.2. Results

Error rates

Mean error rate was 9.36%. The test showed no significant effect of congruency, $t(32) = -0.810$, $p = .424$.[15]

Response times

The test showed a significant effect of congruency, $t(32) = -3.887$, $p < .001$, $d_z = 0.68$. Targets were classified faster if head orientation and target location corresponded ($M = 475.82 \pm SD = 67.87$) than if they did not correspond ($M = 483.07 \pm SD = 69.90$; see Fig. 8).

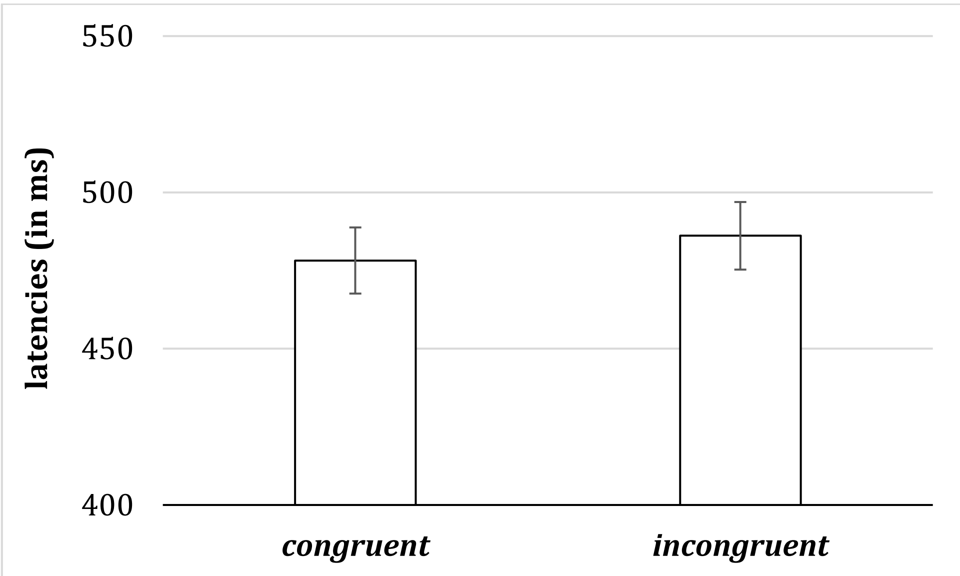

Figure 8. Mean response times as a function of congruency of head orientation shift and target location. Error bars indicate the standard error.

2.1.3 Discussion

Observing a person tilting her/his head up or down from an aligned to a misaligned posture influenced spatial attention orienting in accordance with the additive-contributions account (Langton, 2000) account: Participants classified targets faster in congruent trials, in which targets appeared in the locations cued by the tilted heads. In contrast, participants classified targets slower in incongruent trials, in which targets appeared in the locations opposite to those cued by the tilted heads. According to social cueing accounts (for an overview, see Frischen et al., 2007), this effect can be explained with the preparation of or an *actual* attention re-orienting induced by the observed head

[15] Please note that the absence of effects in the analyses of Experiment 1-3 might be the result of the relatively low number of trials (144 relative to 336 in Experiments 2 and 3 of the publication of Hietanen, 1999). Therefore, the results of the error rate tests of Experiments 1-3 will not be discussed in the remainder of this thesis.

orientation shift and the most diagnostic feature of the final head position (i.e., the head orientation direction of the person in the tilted head picture). Please note that according to gaze-priority accounts (Hietanen, 2002; Perrett et al., 1992), participants should have followed gaze direction, which was slightly opposed to the direction of the head tilts.

Challenging a head cueing account, one might argue that in addition to the orientation shift of the heads, the location of the eyes changed in the tilted-head pictures used in Experiment 1 (see Fig. 6). Therefore, the response time advantages could be the result of a reduction vs. extension of the distances between the attention-drawing eyes (i.e., direct gaze effect, Senju & Johnson, 2009) and the target rather than a head cueing effect. However, the individual contributions of eye position and head orientation alone can hardly be divided out. Thus, to disentangle the individual contribution of head shift from the combined contributions of target distance and misaligned gaze-head posture, Experiment 2 was designed to test the effect of the head movement alone. For that purpose, the order in which tilted head pictures and non-tilted head pictures were presented in each trial was switched relative to Experiment 1.

2.2. Experiment 2

Experiment 2 examined the hypothesis that the observation of vertical head shifts from an up- or down-tilted to a non-tilted position results in response time advantages for target-classifications in congruent relative to incongruent locations. Specifically, congruent locations were understood as those following the direction of the head movement while incongruent locations correspond to the direction of the original head tilts in the first pictures. In each trial, a photograph of a model with the head tilted up or down preceded that of the same person with the head not tilted immediately before the target appeared in addition. Thus, head orientation shifted from a misaligned to an aligned gaze-head posture, which leaves only the head movement as potential effector in the stimulus material.

2.2.1 Methods

Participants

55 volunteers (42 female, 13 male, M = 26.76 years, range: 18-61) from the Würzburg area participated in the experiment. Participants received a financial compensation for study participation. Due to the absence of reliable a-priori knowledge on the expected effect size, we collected data of n = 55 participants. A sensitivity analysis showed that with this sample size, a medium-sized effect of $d_z \geq 0.38$ could be detected with a statistical power of $1-\beta = .08$ in a two-tailed paired-samples t-test with alpha-level = .05 (calculated with G*Power 3.1; Faul et al., 2007).

Apparatus and stimuli

The experiment was run on Computers using Inquisit 5 software (Inquisit 5, 2016). The stimuli were the same as in Experiments 1.

Procedure

The procedure was the same as in Experiment 1 apart from one deviation. Specifically, in Experiment 2 the order of the tilted-head pictures was switched in comparison to Experiment 1. Thus, the fixation cross shown at the beginning of each trial was replaced by the picture of a person with the head tilted up or down after 500 ms. After another 1,000 ms had elapsed, a picture of the same person with the head not tilted replaced the tilted-head picture. The target shape appeared on the screen in addition to the non-tilted head picture another 300 ms later (see Fig. 9).

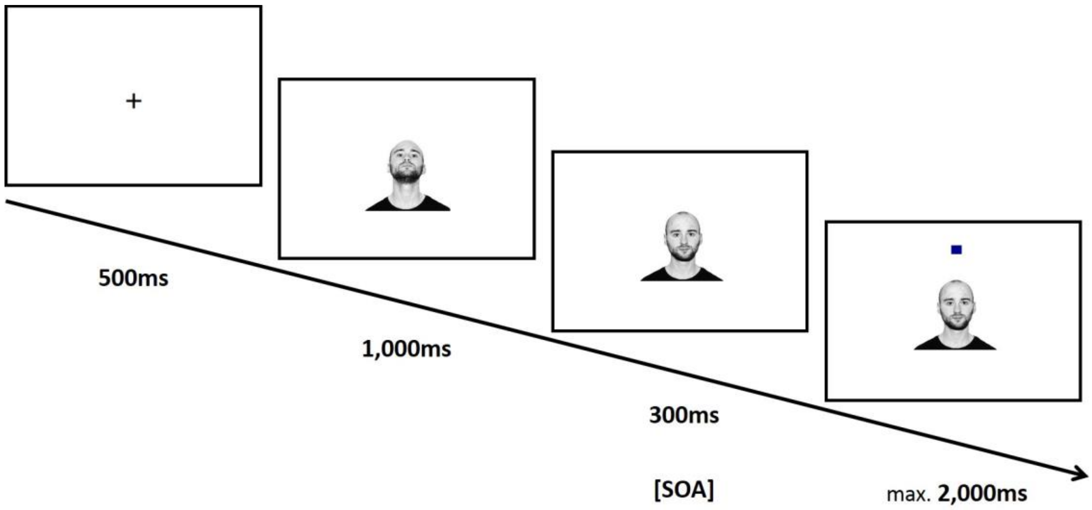

Figure 9. Sequence of events in an incongruent trial of Experiment 2. Please note that in each trial, a tilted head picture preceded a non-tilted head picture of the same person before the target appeared in addition. Participants were instructed to classify the blue target as circle or square using the keys “F” and “J” or vice versa (counterbalanced between subjects).

Data Analysis

Mean RTs and error rates were computed for congruent and incongruent trials. Trials with incorrect responses (2.8% of all trials) were removed from the RT analyses. In addition, 2.6% of trials were removed on the basis of individual Tukey thresholds (Tukey, 1977). The remaining mean response times and mean error rates of congruent versus incongruent trials were submitted to one-sided paired-samples t-tests. The reasoning behind the one-sided test follows the unambiguity of movement direction as only remaining effector in the stimulus material.

2.2.2 Results

Error rates

Mean error rate was 4.9%. The test showed no significant effect of congruency, $t(54) = -0.433$, $p = .666$.

Response times

The test showed no significant effect of congruency, $t(54) = .442$, p =660. The mean response time when direction of head movement and target location corresponded was $M = 466.39 \pm SD = 71.20$. The mean response time when direction of head movement and target location did not correspond was $M = 465.69 \pm SD = 71.94$.

2.2.3 Discussion

Experiment 2 did not show that observing a person tilting her/his head up or down from a tilted to a non-tilted head posture influenced spatial attention orienting: Classification times for targets that appeared in cued vs. opposite-to-cued locations did not differ significantly from each other. Thus, head movement alone did not shift observers' attention to cued locations. Note that in contrast to Experiment 1, head orientation shifted from a misaligned (head tilted up or down, gaze directed at the observer) to an aligned gaze-head posture (both head orientation and gaze are directed at the observer).

A critical question is what process (or combination of processes) was causally responsible for the absence of the expected spatial attention-orienting responses to head movement alone. Based on the change of vertical eye location, one might speculate that the presumed effect of head movement was nullified by the attention drawing direct gaze effect of the non-tilted final head position (Senju & Johnson, 2009). In a similar vein, one might argue that the direction-detection mechanism may have interpreted a shift from a misaligned initial to an aligned final gaze-head posture as resolution of an initial discrepancy (based on motion implied in misaligned gaze-head signals; cf. Pomianowska et al., 2012). In consequence, spatial attention might have been captured at the center of the facial stimuli rather than having been shifted in continuation of the perceived head movement. Alternatively, one might speculate that the cueing effect of the head movement decayed until target onset. After all, participants had to view the non-tilted head pictures for 300ms before a circle or square appeared in addition.

As head movement alone did not affect response times, Experiment 3 foregoes switching between non-tilted and tilted head pictures. Specifically, Experiment 3 employed the photographs of tilted heads alone to test if they shift an observer's attention like the dynamic variant had done in Experiment 1. Thus, Experiment 3 ruled out the possibility of a decay of a head cueing effect due to a waiting period in-between tilted head stimulus and target onset. Moreover, the static tilted head stimuli employed in Experiment 3 are methodologically closer to the procedure used in Hietanen's (1999, 2000) studies (see Fig. 4) than the dynamic variants in Experiments 1 and 2. Please remember that Hietanen (1999, 2002) tested if and how (static) misaligned gaze-head postures affect observers' attention orienting in the horizontal dimension, while the present work addressed the vertical dimension.

2.3. Experiment 3

Experiment 3 examined the hypothesis that the observation of a static up- or down-tilted head posture results in response time advantages for target-classifications in congruent (i.e., head-cued) relative to incongruent (i.e., opposite to the head-cued) locations. In each trial, a photograph of a person with the head tilted was shown immediately before the target appeared additionally. Please note that only up- and down-tilted head pictures were employed in this Experiment. Moreover, due to the unambiguous results of Experiments 1 (i.e., head orientation and not gaze determined attention shift direction) and 2 (i.e., movement alone had no effect), we tested the additive-contributions account (Langton, 2000) alone rather than testing it against the predictions of gaze-priority accounts (Hietanen, 2002; Perrett et al., 1992). As a consequence, the locations in continuation of the respective vertical head tilts were understood as congruent locations (relative to the respective stimuli).

2.3.1 Methods

Participants

28 volunteers from the Würzburg area participated in the experiment. Participants received a financial compensation for study participation. In Experiment 1, the effect size of the effect of down-tilted vs. non-tilted head orientation on spatial attention orienting was $d_z = 0.68$ (one-tailed paired-samples t-test). The a-priori power analysis (calculated with G*Power 3.1; Faul et al., 2007) showed that a minimum of $n = 25$ must be collected for the detection of an analogous effect with a statistical power of $1\text{-}\beta = .95$ (alpha-level = .05; matched-pairs t-test). We therefore collected data of $n = 28$.

Apparatus and stimuli

Experiment 3 was run on laptops using Inquisit 3 software (Inquisit 3, 2007). The priming stimuli for all six Experiments consisted of 54 portrait-like photographs. The stimuli were the same as in Experiments 1 and 2.

Procedure

The procedure was the same as in Experiment 1 apart from two deviations. Firstly, the non-tilted head pictures were omitted. Thus, each trial started with a fixation cross that was replaced by the picture of a person with the head tilted up or down after 1,500 ms. Secondly, the Stimulus Onset Asynchrony (SOA) between stimulus and target appearance was reduced from 300 ms in Experiments 1 and 2 to 200 ms. In consequence, the target shape appeared on the screen 200 ms after the tilted head picture (see Fig. 10). While a mere direct gaze effect should not be affected by shortening the SOA from 300 ms to 200 ms (Conty, Tijus, Hugueville, Coelho, & George, 2006 found direct gaze effects employing SOAs of 150-170ms), the processing of central social cues builds up gradually with a peak effect size at 300 ms (Cheal & Lyon, 1991; Frischen et al., 2007). Thus, Experiment 3 allows for testing the processing speed of participants' assumed attention orienting response.

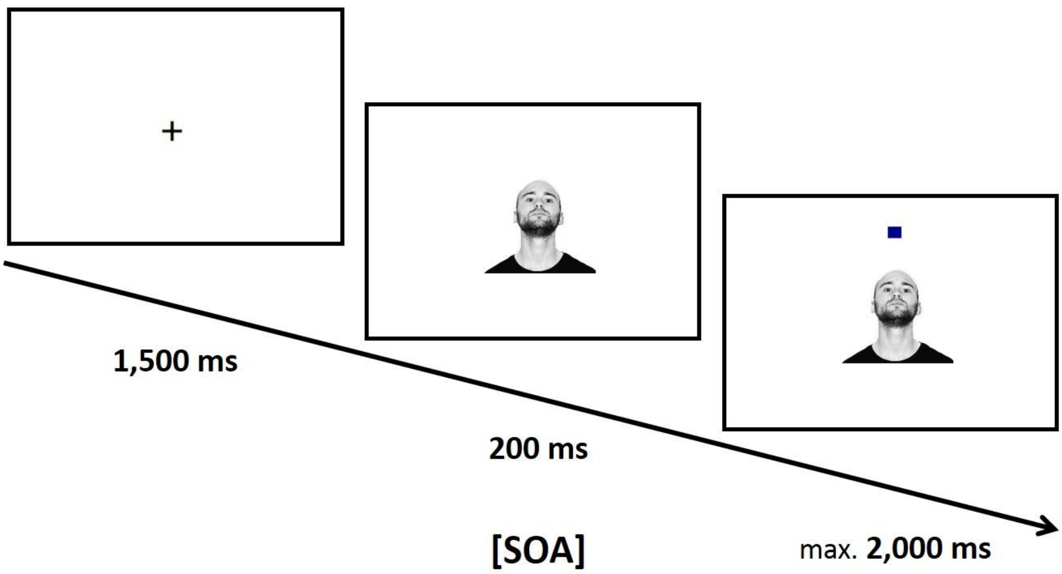

Figure 10. Sequence of events in a congruent trial of Experiment 3. Participants were instructed to classify the blue target as circle or square using the keys "F" and "J" or vice versa (counterbalanced between participants).

Data Analysis

Mean RTs and error rates were computed for congruent (down-tilted head and target below the photograph, up-tilted head and target above the photograph) and incongruent (down-tilted head and target above the photograph, up-tilted head and target below the photograph) trials. Trials with incorrect responses (4.3% of all trials) were removed from RT analyses. Moreover, one participant was removed from the analysis due to his high percentage of incorrect trials (>10% of all trials incorrect). In addition, 1.6% of response times were removed on the basis of individual outlier thresholds (Tukey, 1977). In accordance with our a-priori-hypotheses, the remaining mean response times and mean error rates of congruent versus incongruent trials were submitted to one-sided paired-samples t-tests. The reasoning behind the one-side t-test followed the results of Experiment 1, which were in line with the predictions of the additive-contributions account (Langton, 2000) rather than the gaze-priority (Hietanen, 2002; Perrett et al., 1992) accounts.

2.3.2. Results

Error rates

Mean error rate was 3.94%. The test showed no significant effect of congruency, $t(26) = 0.092$, $p = .928$.

Response times

The test showed a significant effect of congruency, $t(26) = -1.76$, $p = .045$, $d_z = 0.34$. Targets were identified faster if head orientation and target location corresponded ($M = 527.30 \pm SD = 67.62$) than if they did not ($M = 534.75 \pm SD = 72.78$; see Fig. 11).

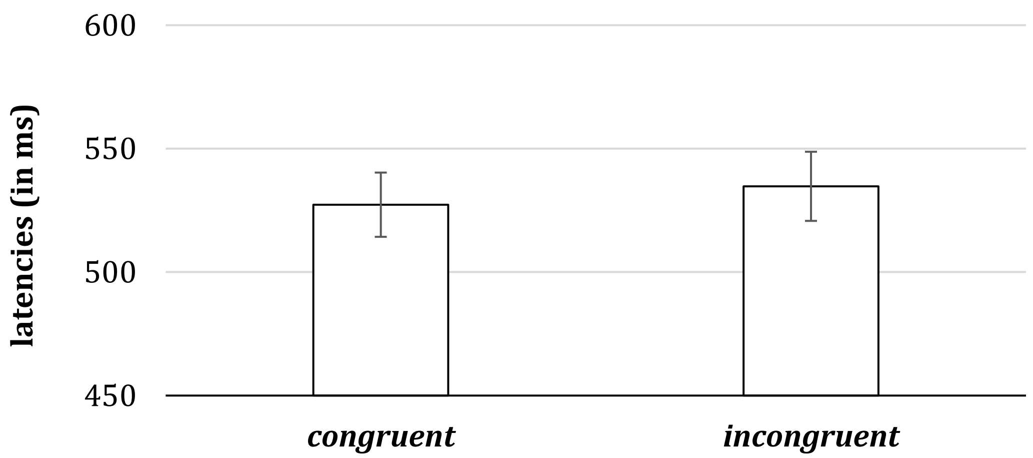

Figure 11. Mean response times as a function of congruency of head orientation and target location. Error bars indicate the standard error.

2.3.3 Discussion

Again, observing a person with head tilted up or down influenced spatial attention orienting in accordance with Langton's (2000) account. Participants classified targets faster in congruent trials, in which targets appeared in the locations cued by the tilted heads. By contrast, participants classified targets slower in incongruent trials, in which targets appeared in the locations opposite to those cued by the tilted heads. Analogue to Experiment 1, this effect can be explained with the preparation of and/or an actual attention re-orienting in accordance with the observed person's head orientation (cf.

Frischen et al., 2007). Note that static cueing stimuli were employed in Experiment 3, i.e. participants viewed the pictures of misaligned gaze-head postures (with the head tilted up or down) alone.

There are two methodological issues to be addressed. Firstly, the static tilted head effect is less pronounced than the dynamic tilting head effect of Experiment 1. However, a mega analysis showed no significant interaction of the two Experiments with the difference between congruent and incongruent trials ($F < 1$). Moreover, the SOA between the appearance of the tilted head picture and the target in Experiment 3 was not only shorter (200 ms) than in Experiment 1 (300 ms), but shorter than the optimum for central social cues to take effect (i.e. 300ms; e.g. Frischen et al., 2007.). Additionally, participants in Experiment 1 first saw a non-tilted head for 1,000 ms, then a change in the picture, and then the tilted head picture for another 300 ms. By contrast, the overall viewing time of the stimulus in Experiment 3 was 200 ms. In consequence, some of the participants might just have ignored the spatial head cues implied in the stimuli. The relatively small number of errors (4.3% of all trials) in comparison to Experiment 1 (7.9% of all trials) is in line with this interpretation of the data.

Secondly, it cannot be ruled out that response time advantages might be the result of a reduction vs. extension of the distances between the attention-drawing eyes (Senju & Johnson, 2009) and the target rather than a head cueing effect. However, one need not take a firm stance here, as complementing effects of eye position and head direction could be responsible for the effects as well. Nonetheless, a direct gaze effect does not need as much processing time (Conty et al., 2006) as the interpretation of the more complicated gaze-head postures (Cheal & Lyon, 1991; Frischen et al., 2007), which is why the reduced effect size in comparison to Experiment 1 slightly favors a tilted head explanation.

2.4 Discussion of Experimental Series A

Experimental Series A investigated effects of vertically misaligned gaze-head constellations with gaze directed at the camera on an observer's spatial attention orienting. Experiment 1 showed that participants classified targets faster after they had observed a head movement from a non-tilted to a tilted position that cued the target location relative to one that cued the opposite location. Experiment 2 showed no such classification time advantages when participants had observed head movements from tilted to non-tilted positions. Experiment 3 showed classification advantages for targets appearing in locations cued by static tilted head postures relative to those appearing in opposite locations. Both head cueing effects were independent of the observed person's actual direction of attention, as s/he always gazed at the observer. In short, the observation of another person with her/his head tilted up or down seems to increase the accessibility of corresponding spatial codes in both dynamic and static stimuli setups.

2.4.1 Effects of head cueing on spatial attention

Langton's (2000) additive-contributions account that suggests an independent and additive processing of gaze and head information seems most suitable to account for the vertical head cueing effects found in Experiments 1 and 3. Specifically, this integrative account predicted an effect of head orientation alone as direct gaze added no additional spatial information for the computation of the observed person's (current or anticipated) direction of attention. By contrast, Hietanen's (2002) as well as Perrett and colleagues' (1992) gaze-priority accounts predicted the opposite pattern of results, because they assume a hierarchical processing of gaze and head information. According to their gaze-prioritizing accounts, the direction-detection system should have processed the directional information of the direct eye gaze within the context of the tilted head postures. In consequence, attention should have *overshooted* to the location opposite to that indicated by head orientation due to the slightly opposing direction of the eyes (within the context of the tilted heads; see Fig. 6, Fig. 5, and Fig. 4). However, these gaze-prioritizing predictions were ruled out by the results of Experiments 1 and 3.

What process or combination of processes triggered by the dynamic head orientation stimuli was causally responsible for the congruency effect in Experiments 1 and 3? This question is especially critical since the mechanism was absent in Experiment 2. Based on social cueing research, two explanations might plausibly account for the present findings. Firstly, spatial concepts were suggested to be automatically applied to another's nonverbal cues (gaze, head, body, gestures) during encoding to retrace what the observed person is attending to (e.g. Langton & Bruce, 2000; Perrett, Smith, Potter, Mistlin, Head, Milner, & Jeeves, 1985; Jenkins & Langton, 2003). This explanation would imply that every nonverbal gaze or body signal that is encoded in a spatial reference frame can bias spatial attention orienting (Hietanen; 2002; Langton & Bruce, 2000; Langton et al., 2000). Note that bodily signal at this point means that the social stimulus contains an ostensive cue (Böckler et al., 2011; Hietanen, 2002) and implies motion (e.g. Pomianowska et al., 2012; see absence of cueing effect in Experiment 2). Moreover, this explanation is in line with sensory-motor simulation theories (Gallese & Goldman, 1998; Jeannerod, 2001), which argue that perceiving others' bodily action(s) or state(s) is simulated in one's own motor system.

Secondly, an alternative account would explain the effect with systematic differences in the distance between the target and the position of the eyes in the pictures. More precisely, lowered and elevated head postures corresponded with a slightly lowered and elevated positioning of the eyes. Therefore, the distance between the fixated eyes and the target could have been reduced or extended in a corresponding way. This explanation would be based on the preferential fixation of eyes during interpersonal contact, especially when eye contact is established by the interaction partner (direct gaze effect; e.g. Senju & Johnson, 2009). As a consequence, systematic attention shifts to lowered or elevated positions that aimed at fixating the eyes of the person in the picture could be responsible for the effect. Please note that up- vs. down-tilted head and elevated vs. lowered eye positions were present in both Experiment 1 and 3, but not in the final picture of Experiment 2. Alternatively, one might argue that a combination of the two accounts might have been involved in activating spatial codes in the observer's direction-detection system, which in turn triggered corresponding shifts of attention.

Nonetheless, several arguments slightly favor an explanation based on head cueing over an explanation based on distance to position of eyes. Firstly, if the latter explanation held true, results in Experiment 3 should have been similar to those in Experiment 1. After all, the distance-based effect is based on the direct gaze effect, which was shown for SOAs below 200 ms (e.g. Senju & Johnson, 2009). By contrast, perceiving central social cues like complex gaze-head misalignments affords a certain duration of processing time to take effect with a peak at 300 ms (e.g. Cheal & Lyon, 1991; Frischen et al., 2007). Thus, a head cueing explanation is compatible with tracing the reduced effect size of Experiment 3 (relative to that in Experiment 1) back to its reduced SOA of 200 ms, while a distance-based is not. Secondly, gaze-priority accounts (Hietanen, 2002; Perrett and colleagues, 1992) predicted effects opposite to those found in Experiments 1 and 3, which makes it unlikely that an explanation based on distance to position of eyes holds true. Finally, considering the speed of saccades (Robinson, 1964), differences in fixation positions between the two types of tilted head pictures constitute no parsimonious alternative explanation to a head cued re-orienting of attention to the upper or lower parts of the picture.

Finally, Experimental Series A has implications for how observers respond to others' peripersonal space representation. After all, the angles of the tilted heads implied salient and strong changes in the visual field of the pictured persons affecting head-centered near space representation accordingly (e.g. Cléry et al., 2015; Holmes & Spence, 2004). At the same time, the direct gaze of the pictured persons indicated both that their attention is oriented towards the observer and the lower or upper section within their upward or downward oriented visual field, respectively. Consequently, the prioritized effect of head orientation (relative to actual gaze direction) in the vertical dimension means that the participants responded to the observed persons' visual field rather than the actual focus of attention (Experiments 1 and 3). Please note that the targets appeared within all of the observed persons' peripersonal space. I will elaborate on these considerations in the General Discussion.

2.4.2 Methodological considerations and future research

The present experiments have some limitations. Firstly, The SOA was fixed at short durations of 300 ms (Experiment 1 and 2) to 200 ms (Experiment 3) rather than varying between several durations. One advantage of this approach was that inhibition of return effects were prevented by the SOA durations employed in Experiments 1-3. For longer cue-target intervals, however, inhibition of return effects were shown to impair speed and accuracy of target detection in several spatial cueing experiments (e.g. Maylor, 1985; Maylor & Hockey, 1985; Posner & Cohen, 1984). Secondly, the present studies did not dissociate the position of the eyes and the direction of the head tilt. In future experiments tilted head pictures with closed eyes could be used to further substantiate the effects of head orientation on observers' spatial attention orienting. However, this approach might risk the ostensive quality of the present stimuli with the eyes signaling to the observer that s/he is the addressee of a communicative intent (e.g. Böckler et al., 2011). Moreover, critics of social cognition interpretations could employ non-tilted head stimuli alone and shift their vertical position across trials to test the sole effect of distance between position of eyes and target. From a social cueing perspective, however, this approach would only be successful if participants realized the changes and assumed intentionality (cf. Frischen et al., 2007).

Finally, it is important to note that the head cueing effects in response to misaligned gaze-head postures in the vertical dimension oppose those previously shown in the horizontal dimension (Hietanen, 1999; Moors et al., 2015; Pomianowska et al., 2012). This may suggest different processing modes for processing vertical vs. horizontal social spatial information. However, these differences in attentional response might also be the result of deviating interpretations of the motion implied in vertically vs. horizontally oriented misaligned gaze-head postures (e.g. Pomianowska et al., 2012). After all, the vertical vs. horizontal extent of the visual field are not identical as the horizontal angle is large than the vertical one. I will elaborate on this point in the General Discussion. Future studies might further elucidate the processes involved in the direction-detection mechanism by testing the respective influences of gaze direction, head orientation and body posture in both static and dynamic experimental setups against each other.

3 | Experimental Series B: Head cueing of numerical magnitude[16]

Experimental Series B investigated whether the attention orienting effect in response to another person's vertical head orientation - as demonstrated in Experimental Series A - extends to numerical magnitude processing. In Experiment 4, participants generated random numbers after viewing photographs of people with the head tilted up, down, or not tilted (RNG; Evans, 1978). In Experiment 5, participants answered numerical trivia questions with more complex number ranges (from one- to five-digit numbers) after having had seen photographs with heads tilted down or not tilted. Note that in both experiments the head orientation pictures were no longer present during the numerical cognition task. In Experiment 6, participants used two response keys to judge if a given number was smaller or larger than five in number trials and could freely decide between the same two keys in picture trials. In these trials, viewing a person with his/ her head tilted up or down indicated a free response decision. It was hypothesized that participants respond to persons with heads tilted down (up) with smaller (larger) numerical magnitudes than to persons with head tilted up (down) or not tilted, irrespective of whether their response afforded pressing a numerical key (Experiment 1), typing a multi-digit number (Experiment 2), or freely choosing between two keys that were associated to numerical magnitude via intermixed numerical magnitude judgment tasks (Experiment 3).

3.1 Experiment 4

Experiment 4 examined the hypothesis that the passive viewing of down- and up-tilted faces primes the generation of smaller and larger numbers, respectively, in a manual RNG task. In each trial, a photograph of a model with the head tilted up, down, or not tilted was presented for a short time immediately before the RNG task. In line with the notion of a vertically oriented mental number line (e.g. Winter et al., 2015), it was hypothesized that smaller numbers are produced in response to the down-tilted head pictures and larger numbers in response to the up-tilted head pictures relative to each other and the non-tilted control stimuli. Please note that due to the suggested logarithmic-like shape of the mental number line (e.g. Dehaene & Changeux, 1993; Dehaene et al., 1993), smaller numbers up to 4 should be represented more precisely than larger numbers, which rendered an effect of down-tilted head stimuli more likely than an effect of the up-tilted head pictures (small number bias, e.g. Banks & Hill, 1974; Loetscher & Brugger, 2007). Moreover, Experiment 4 dissociated the social cueing stimuli from the number generation

[16] Please note that Chapter 3 is based on the publication Götz, F. J., Böckler, A., & Eder, A. B. (2019). Low numbers from a low head? Effects of observed head orientation on numerical cognition. *Psychological research,* 1-14, which was published online in June 2019, i.e. after this thesis was handed in.

task by presenting them sequentially instead of simultaneously (cf. Fischer & Shaki, 2016).

3.1.1 Methods

Participants

Sixty-one volunteers (44 female, 17 male, M = 26.23 years, range: 19-59) from the Würzburg area participated in the experiment. Participants received a financial compensation for study participation. Due to our uncertainty about the expected effect size, data of n = 61 participants were collected. A sensitivity analysis showed that with this sample size, a medium-sized effect of $f(U) \geq 0.28$ (effect size specification as in SPSS) could be detected with a statistical power of 1-β = .80 in a repeated measures analysis of variance (ANOVA) with three measurement levels and alpha-level = .05 (calculated with G*Power 3.1; Faul et al., 2007).

Apparatus and stimuliThe experiment was run on laptops using Inquisit 3 software (Inquisit 3, 2007). The tilted head stimuli were the same as in Experiment 1 (see Fig. 6 and Fig. 12). An additional set of 36 photographs (18 models, 9 male, two pictures per person) was selected from the Radboud Faces Database (Langner, Dotsch, Bijlstra, Wigboldus, Hawk, & Knippenberg, 2010) for catch trials in which participants should not respond. The pictures were matched in size and color with the tilted head pictures described above. Half of the pictures showed the model with a clear body orientation (including head and gaze) to the left and the other half with a clear body orientation to the right (see Fig. 12). Please note that in Hietanen's (1999, 2002) studies, analogous pictures did not affect the observers' attention orienting, presumably because there were no ostensive cues (like gaze and/or body directed at the observer) that would signal to the observers that they are the addressees of a communicative intent (e.g. Böckler et al., 2011; Csibra & Gergely, 2009; based on Sperber & Wilson, 1986).

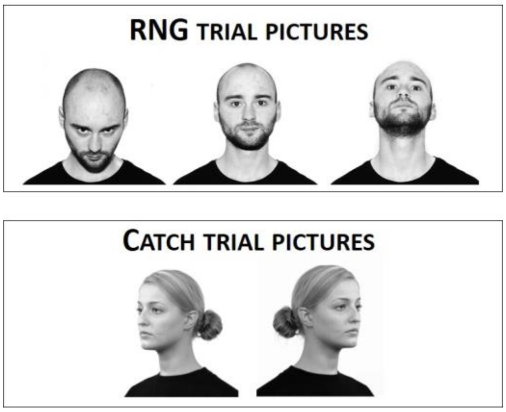

Figure 12. Examples of the two types of pictures employed in in Experiments 4. Please note the clear body orientation (including head and gaze) to the left vs. right of the models in the Catch trial pictures (lower row). The RNG pictures (upper row) were the same used in Experiments 1-3.

Procedure

A trial started with the picture of a person that was replaced by a fixation cross after 1,500 ms. Thus, the head orientation picture was not visible while the participants responded. The fixation cross was displayed until response registration or until 3,000 ms (2,000 ms in the catch trials) had elapsed (see Fig. 13). In case of an incorrect or omitted response, an error message appeared for 2,500 ms. The next trial started after 700 ms.

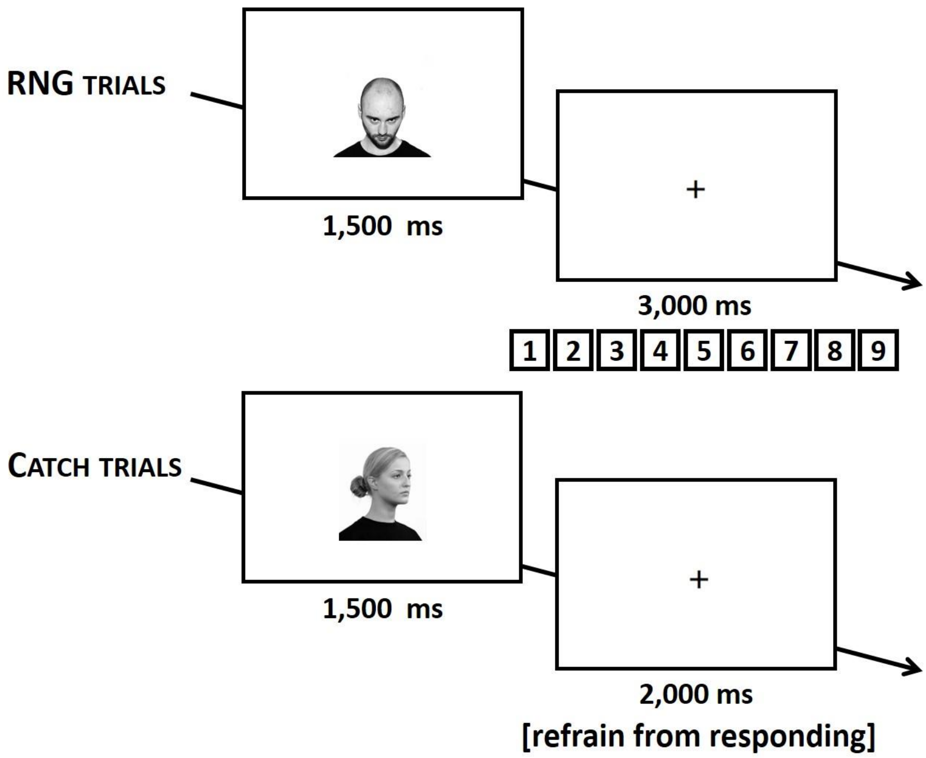

Figure 13. Sequence of events in experimental (RNG; top) and catch (bottom) trials of Experiment 4. Participants were instructed to press one of the numerical keys on the top row of the keyboard only if the displayed model looked directly at the participant (eye contact).

Instructions for the RNG task were to generate a one-digit number when the model in the photograph is shown from the front (experimental trials) and to not respond when the model is oriented to the left or right (catch trials). Thus, the photographs were relevant to identify experimental trials. Catch trials were randomly intermixed to discourage participants from strategic number generation before the picture presentation. Participants were explicitly instructed to spontaneously generate a random number and to avoid a systematic sequence or pattern. The metaphor of an urn containing the 9 numbers was used to illustrate the selection of a random number (cf. Baddeley, 1966; Grade et al., 2013; Loetscher & Brugger, 2007). The one-digit number was entered with the numerical keys (1-9) on the top row of the keyboard. Instructions for the catch trials were to wait until the trial had ended.

The experiment had one practice block with 6 trials and three experimental blocks with 36 trials each. Half of the trials in a block were catch trials. In the 18 experimental trials of a block, the three types of tilted-head pictures (up-, down-, non-tilted) were presented in random order, showing one photograph of each of the 18 models in every block. In the 18 catch trials of a block, each model was shown once with either a left or a right body orientation. Participants had a short rest period after each block with a reminder of the task instructions.

Data Analysis

The mean of the self-generated numbers was computed for each head orientation (down-tilted, non-tilted, up-tilted). These mean numbers were submitted to a one-factorial repeated-measures analysis of variance (ANOVA) with observed head orientation (down-tilted, non-tilted, up-tilted) as within-subject factor. In case of significant main effects and in accordance with our a priori hypotheses, the data was subsequently submitted to one-sided paired-samples t-tests.

3.1.2 Results

The ANOVA showed a significant main effect of head orientation, $F(2, 59) = 4.57$, p = .012 η_p^2 = .071. Subsequent t-tests showed that numbers generated after a down-tilted head (M = 4.86 ± SD = 0.89) were significantly lower compared to those generated after non-tilted heads (M = 5.25 ± SD = 0.62), $t(60)$ = -2.86, p = .006, d_z = 0.37, and up-tilted heads (M = 5.16 ± SD = 0.79), $t(60)$ = -2.07, p = .043, d_z = 0.27 (see Fig. 14). Numbers generated after up-tilted heads did not differ from the control condition with non-tilted heads (t < 1).

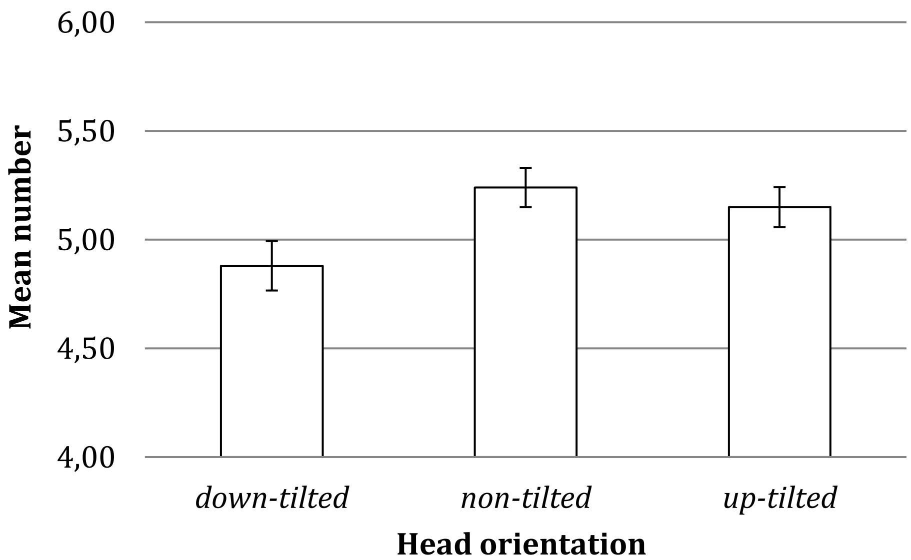

Figure 14. Mean numbers produced in Experiment 4 as a function of the model's head orientation. Error bars indicate the standard error.

3.1.3. Discussion

Observing a person with head tilted down influenced number generation in accordance with the hypothesis, i.e. participants produced smaller numbers in the down-tilted head trials relative to a control condition with non-tilted head orientations. Following the interpretation of Grade and colleagues (2013), this effect can be explained with a transfer of the attention shift that is induced by the head-orientation pictures in perceptual space to the mental number line. As a consequence, smaller numbers were more accessible in memory following the perception of a down-tilted head picture. By contrast, observing the same person with the head tilted up did not significantly affect random number generation relative to the control condition. This finding is in line with past research by Grade and colleagues (2013) as well as other researchers (e.g. Hartmann et al., 2012; Loetscher et al., 2008). Moreover, it can be ascribed to the logarithmic-like distribution of numbers along the mental number line that was suggested by several authors (e.g. Dehaene & Changeux, 1993; Dehaene et al., 1993). According to them, the mental number line allocates more space to smaller numbers and less to larger numbers (and/or numerosities), which allows for a more precise processing of the former relative to the latter (resulting in a small number bias, e.g. Banks & Hill, 1974; Loetscher & Brugger, 2007).

An alternative explanation by Proctor and Cho (2006) challenges the attention shift account outlined above with the notion of "polarity correspondence". This is noteworthy due to the fixed spatial arrangement of the numerical response keys on the keyboard with smaller numbers to the left and larger ones to the right. In consequence, a match between the polar dimensions *downward tilt* and *left-sided response location* could have facilitated corresponding response sets on the left side (see also Roettger & Domahs, 2015). To test this alternative account, I conducted Experiment 5. In this experiment, an anchoring-like numerical estimation task with multi-digit number ranges was used that de-confounded quantity estimates from particular response locations.

3.2 Experiment 5

Experiment 5 examined effects of vertical head orientations on estimates of quantities in a modified anchoring paradigm. Many studies showed that the presentation of a numerical value (the anchor) before a difficult numerical trivia question affects judgments under uncertainty, with larger estimates following large values and smaller estimates following small values (Tversky & Kahneman, 1974; for a review see Furnham & Boo, 2011). In experiment 5, I adjusted the anchoring paradigm, so that the depicted person, who supposedly provided the numerical anchor, was presented *just before* the trivia question (but not simultaneously; for a similar procedure, see Erle & Topolinski, 2017). Importantly, the person supposedly providing the numerical anchor was presented either with the head tilted down or with the head in a straight position. Models with an up-tilted head were not included in this experiment to reduce the overall number of trials. This procedure allowed us to present pictures of persons in a meaningful social context whilst manipulating their vertical head orientation. It was hypothesized that the model's head orientation operates like an anchor value for the subsequent numerical judgment. Accordingly, numerical answers to the trivia questions should be smaller after having viewed a model with a down-tilted head. Note that the numerical estimate provided by the person in the picture was only used to center the participants' numerical judgments around a fixed value to restrict the variance of their quantity estimates (cf. Eerland et al., 2011). In addition, the numerical estimate provided by the model was varied between questions (and not across participants as in classical anchoring studies; e.g. Strack & Mussweiler, 1997).

3.2.1 Methods

Participants

Eighty-five students (48 female, 35 male, 2 indicated no gender, M = 25.64 years, range: 16-79) from the University of Würzburg participated for compensation with a chocolate bar. In Experiment 1, the effect size of the effect of down- vs. non-tilted head on number generation was d_z = 0.37 (one-tailed paired-samples t-test). The a-priori power analysis (calculated with G*Power 3.1; Faul et al., 2007) showed that a minimum of n = 81 must be collected for the detection of an analogous effect with a statistical power of 1-β = .95 (alpha-level = .05; matched-pairs t-test). Therefore, data of n = 85 was collected.

Apparatus, stimuli, and procedure

Apparatus and stimuli were identical to those in Experiment 4. Only pictures with down-tilted and non-tilted head orientations (20 pictures each) were taken from the set of 21 photographs described in Experiment 1. For the anchoring-like paradigm, 20 numerical trivia questions (e.g. *How many popes have there been?*) were developed and pretested in a short pre-study with 40 participants. The numerical anchor values provided for the 20 questions were the mean estimations given by the participants in the pre-study.[17]

[17] In classical anchoring paradigms, participants have to answer a comparative trivia question first (e.g. "Have there been more or less popes than [anchor] in the history of the Roman Catholic Church?"). The anchor employed in this question is a number that has an extremely large [85th percentile of the responses in the prestudy] or small [15th percentile of the responses in the prestudy] value relative to the true value/mean of the estimates in the prestudy. A myriad of studies showed that the magnitude of the anchor biases numerical processing and ,as a consequence, numerical judgments under uncertainty (e.g. Tversky & Kahneman, 1974; Strack & Mussweiler, 1997). However, not only numerical anchors but non-conceptual information like endogenous body posture manipulation (Eerland et al., 2011) or social information on the provider of an anchor (Erle & Topolinski, 2017) were shown to influence numerical processing.

In addition to a task and questions unrelated to the present hypothesis, the experiment consisted of a single block with 20 trials. Each picture was displayed only once in a session. Half of the persons had a down-tilted head orientation and the other half were presented with a non-tilted head position. The selection of models showing a down-tilted versus non-tilted head orientation and the assignment of the trivia questions were randomized. A trial started with the presentation of a photograph that was replaced after 1,500 ms by one of the trivia questions next to a numerical estimate supposedly given by the person shown in the preceding photograph. Participants were asked to enter their own numerical estimate into a field box that was positioned at the center of the screen. The question and the person's numerical estimate were presented on the screen until the participant entered her/his numerical judgment (see Fig. 15). As in Experiment 4, the photograph was not visible while participants responded. Head picture presentation time was 1,500ms.

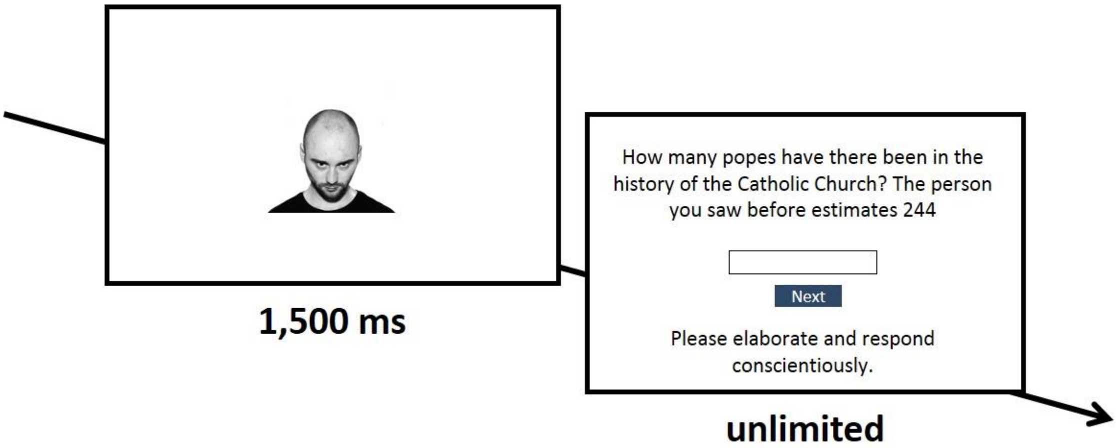

Figure 15. Events in a trial of Experiment 5. A model with her head tilted down or not tilted was presented first who supposedly provided an estimate for a subsequent numerical trivia question.

Instructions for the trivia question task additionally varied depending on how conscientiously participants should think about their answers to the trivia questions. Several authors (Bahnik & Strack, 2016; Simmons, LeBoeuf, & Nelson, 2010) posited that the classical anchoring effect is the result of different processes working in parallel. However, little is known about the circumstances that favor numerical over semantic processes (e.g. Bahnik & Strack, 2016). As many questions presented in anchoring studies are difficult, participants must guess a numerical value in the end. Nonetheless, this guess may involve different degrees of elaboration. Thus, the extent of semantic knowledge involved in the numerical estimate should depend on the degree of conscientiousness that participants invest in seeking for an appropriate answer (e.g. by searching for knowledge about similar or analogue facts). In Experiment 5, participants were randomly assigned to either a conscientious or a spontaneous processing condition (between-subjects design) to investigate the influence of conscientiousness on the influence of head cueing on numerical estimates. A spontaneous or conscientious search mode for the quantity estimate was highlighted in the task instructions and at the bottom of every trivia question slide ("*Please respond as spontaneously as possible*" vs. "*Please elaborate and respond conscientiously*").

Data Analysis

The numerical estimates for each trivia question were z-transformed. Mean z-scores were computed for each head orientation (down-tilted, non-tilted) and submitted to a two-factorial mixed ANOVA with head orientation (down-tilted, non-tilted) as within-subject factor and level of elaboration (spontaneous vs. conscientious) as between-subject factor.

3.2.2 Results

Data of two participants were lost due to computer crashes. The ANOVA showed a significant main effect of head orientation, $F(1, 81) = 4.61$, $p = .035$ $\eta_p^2 = .054$, with mean estimates following down-tilted heads ($M = -.06 \pm SD = 0.32$) being significantly smaller relative to those made after presentations of a non-tilted head ($M = .06 \pm SD = 0.36$; see Fig. 16). Task instructions to respond conscientiously versus spontaneously had no effect, $F(1,81) = 1.05$, $p = .308$. There was no interaction effect ($F < 1$).[18]

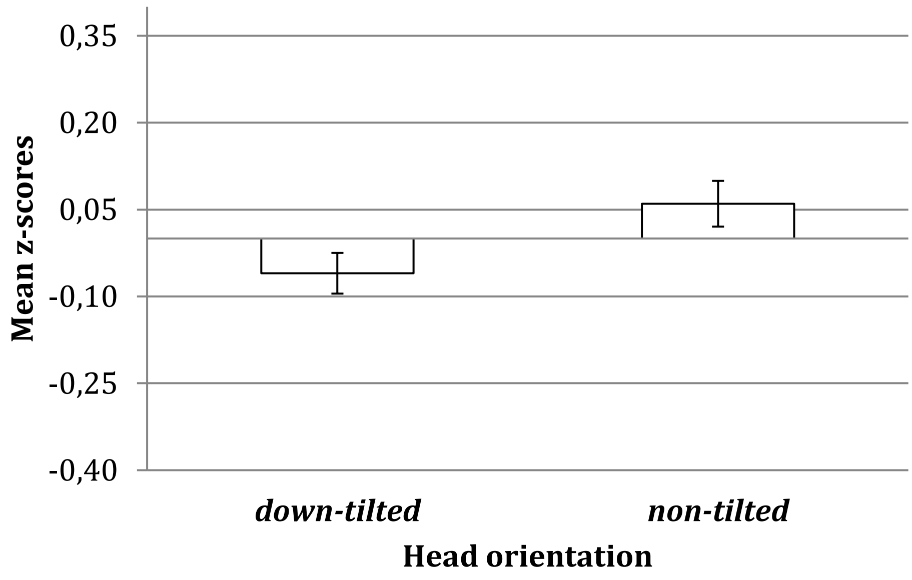

Figure 16. Mean z-scores of the numerical estimates in Experiment 5 as a function of the model's head orientation. Error bars show the standard error.

[18] As a manipulation check for the level of elaboration, the mean response latencies for all participants were calculated and submitted to an independent-samples t-test. Participants who had been instructed to respond conscientiously (M = 17,949ms ± SD = 7,696ms) took significantly more time to come up with an estimate than participants who had been instructed to respond spontaneously (M = 13,996ms ± SD = 4,638ms), $t(81) = -2.789$, $p = .007$, $d_s = 0.62$. Thus, the instructions significantly affected response latencies.

3.2.3 Discussion

As hypothesized, viewing a down-tilted head orientation influenced participants' quantity estimations to the numerical trivia questions: Estimates were smaller after participants had viewed a person depicted with a lowered head position. In contrast to the previous experiment (with the RNG task) the range of generated numbers was larger and more varied, ranging between one-digit to five-digit numbers. Typing multi-digit numbers involved key presses on different locations of the keyboard. Therefore, a polarity correspondence relation (Proctor & Cho, 2006) between vertical head orientations and left-right response locations on the keyboard does not seem to be a plausible account of the head-orientation effect observed in this experiment.

Please note that the degree of elaboration did neither modulate the head orientation effect nor directly affect the estimates given by the participants. Regarding the answering of numerical trivia questions, several authors (Bahnik & Strack, 2016; Simmons, LeBoeuf, & Nelson, 2010) argue in favor of a variety of processes working in parallel, while research has focused on content-based (e.g., Mussweiler, 2003; Strack & Mussweiler, 1997) and numerical (Critcher & Gilovich, 2008; Wilson, Houston, Etling, & Brekke, 1996) mechanisms so far. The absence of additional effects support a numerical cognition rather than a content-based (e.g. Mussweiler, 2003; Strack & Mussweiler, 1997) interpretation of the data at hand. One reason for the absence of content-based influences might be the medium rather than extreme anchors employed for each question. Moreover, the questions were designed to be especially difficult, which might have resulted in randomly generated estimates due to the absence of applicable conceptual knowledge (cf. Bahnik & Strack, 2016)- a strategy similar to RNG in Experiment 1.

3.3 Experiment 6

Experiments 4 and 5 suggest an intimate link between the perceived spatial head orientation of another person and one's own numerical cognition. However, the nature of this link is less clear, as the response keys were spatially distributed from left to right in both experiments. Accordingly, it is possible that the effects observed in Experiments 1 and 2 were - at least partially - the result of a methodological artifact. In Experiment 6, I therefore measured the effect of head orientation on numerical judgment with a more indirect measurement task that dissociated the cueing stimuli from the numerical task. For a better control of the influence of response key location, the association between response key and its meaning in terms of magnitude judgment was manipulated in addition (cf. critique of Fischer & Shaki, 2016).

In Experiment 6, participants worked on two tasks that were mixed and presented in random order: (1) A reaction time task with speeded categorizations of digits into (a) smaller than five or (b) larger than five and (2) a free choice task in which participants could freely select between two response key. Importantly, the same set of response keys were used for both tasks. The number categorization task was used to create short-term associations between the two keys and small vs. large numbers, which transferred to the free-choice task (for related setups, see Daar & Pratt, 2008 and De Houwer, Beckers, Vandorpe, & Custers, 2005). Note that the task instructions for the free-choice task had no explicit mapping of numbers (or categories of numbers) to the response keys. Consequently, for a systematic effect of vertical head orientation on the response choices in the free choice task, participants must have inadvertently applied the key-number associations established in the first task to the response choice in the second task. It was expected that participants would select the response key associated with large numbers less frequently following presentations of down-tilted head pictures relative to presentations of up-tilted head pictures (and vice versa with presses of the response key associated with small numbers).

3.3.1 Methods

Participants

Forty-three volunteers (30 female, 13 male, age = 24.63, range 18-47) participated and received financial compensation for study participation. Due to the absence of reliable a-priori knowledge on the expected effect size, data of n = 43 participants was collected. A sensitivity analysis showed that with this sample size, a medium-sized effect of $d_z \geq 0.38$ could be detected with a statistical power of 1-β = .80 in a matched-samples t-test with the alpha-level set to .05 (calculated with G*Power 3.1; Faul et al., 2007).

Apparatus, stimuli, and procedure

Apparatus was the same as in Experiment 4. Stimuli were the same as in Experiment 1. In the number categorization task, a digit (1-9 excluding 5) appeared in Tahoma font at the center of the screen for 2,500 ms or until response registration. Half of the participants were instructed to categorize the digit as quickly and as accurately as possible into smaller or larger than five by pressing the “F” and “J” keys of the keyboard, while the assignment was reversed for the other half of the participants. In the trials of the free-choice task, a picture depicting a person with a down-tilted or up-tilted head was shown for 2,500 ms or until one of the two response keys was pressed (see Fig. 17). Instructions for this task highlighted that there was no correct response for this task and that participants could freely decide which response key they wanted to press (for a similar free choice instruction, see Daar & Pratt, 2008). After an incorrect response (in the number categorization task) or no keypress, a corresponding error message appeared for 2,500 ms. The next trial was initiated after a variable inter-trial interval (400-800 in steps of 100 ms).

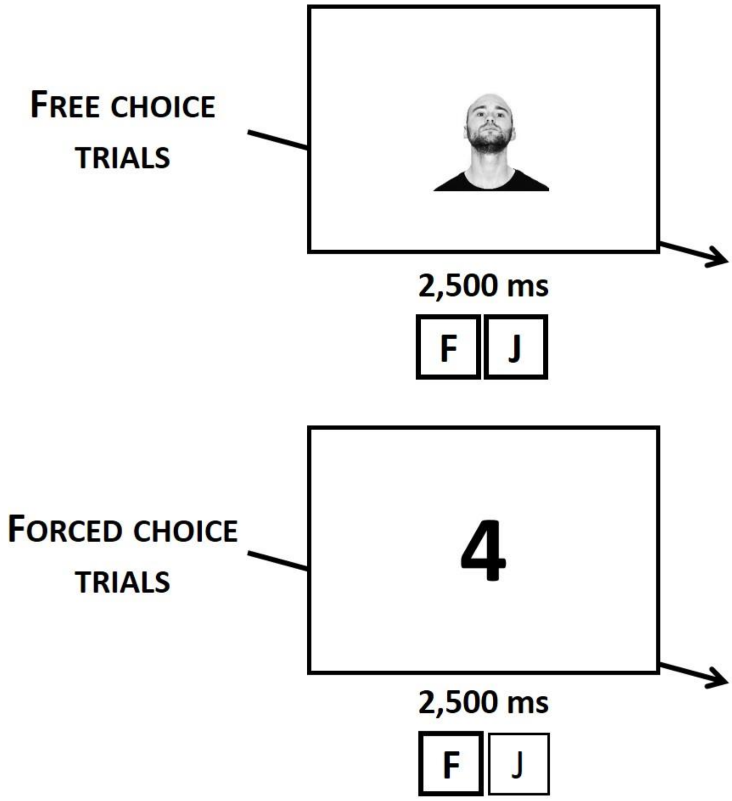

Figure 17. Free choice (top) and forced choice (bottom) trials that were randomly intermixed in Experiment 6.

The experiment consisted of 8 practice trials and three experimental blocks with 36 trials each (total of 108 trials). Within each block, half of the trials were free-choice trials (with picture presentations) and the other half were number categorization trials (with digit presentations). Pictures with straight head positions were not included in this experiment to maximize effect size. Trials and stimuli were presented in random order. Only one of the two pictures of a model was presented in a block. A short resting period with a reminder of the task instructions was allowed between blocks.

Data Analysis

For the free choice trials, the proportion of 'larger'-key presses was computed and submitted to a two-factorial mixed-factor ANOVA with head orientation (tilted downwards vs. tilted upwards) as within-subjects factor and number association (small-left/large-right key association vs. small-right/large-left key association) as between-subjects factor.

3.3.2 Results

Number categorization task

The proportion of correct numerical magnitude categorizations per participant ranged from 76% to 100% (M = 94.83 % ± SD = 4.48%).

Free-choice task

A response was omitted in 0.3% of the trials because the 2,500ms deadline elapsed before the participant provided a response. The ANOVA showed a significant main effect of head orientation, $F(1,41) = 7.33$, $p = .010$ $\eta_p^2 = .152$. The key associated with larger numbers was selected less frequently following presentations of down-tilted heads (M = 0.45 ± SD = 0.24) relative to presentations of up-tilted heads (M = 0.54 ± SD = 0.24; see Fig. 18). The main effect of number-response association was also significant, $F(1,41) = 5.68$, $p = .022$, $\eta_p^2 = .122$. The key associated with larger numbers was chosen less frequently when located to the left (M = 0.42 ± SD = 0.26) relative to the right (M = 0.57 ± SD = 0.12; see Fig. 18). The interaction between both factors was not significant, $F(1,41) = 1.87$, $p = .179$.

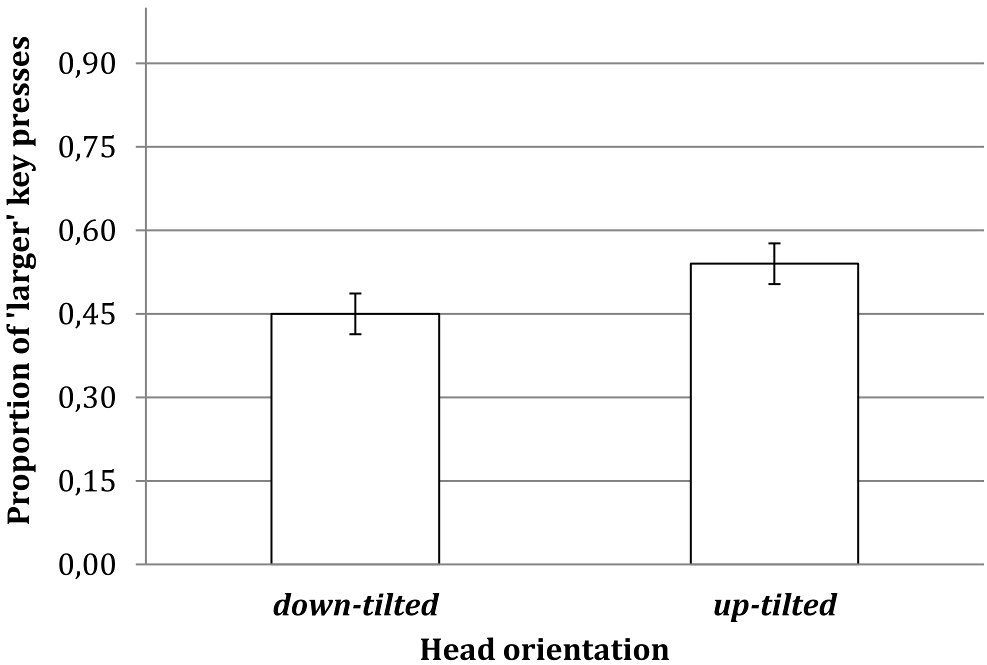

Figure 18. Proportion of 'larger' key presses (in %) in Experiment 6 as a function of the model's head orientation. Error bars indicate standard errors.

3.3.3 Discussion

The models' head position influenced response choice in accordance with the hypothesis: The response key associated with larger numbers was pressed more frequently after observing a person with an up-tilted head relative to a down-tilted head. Importantly, this effect was obtained although number processing was irrelevant for the task at hand. Moreover, the head-orientation effect was not mediated by the spatial arrangement of the two response keys on the horizontal axis, arguing against an explanation based on the concept of polarity correspondence (Proctor & Cho, 2006). Instead, I propose that the effect of head orientation on the response choice resulted from the activation of spatial codes in a shared cognitive system that is accessed by both person perception and representations of magnitudes.

Notwithstanding this explanation, it should be noted that there was a main effect of the number-response key mapping: The right (left) key was pressed more frequently when the response key was mapped onto the larger (smaller) number category in the number classification task. This SNARC-like effect points at a correspondence relation between left responses and small magnitude on the one hand and right responses and large magnitude on the other hand (see Wood, Nuerk, & Willmes, 2006) that is perfectly in line with the polarity correspondence principle (Proctor & Cho, 2006) as well as embodied spatial-numerical associations in the horizontal dimension (e.g. Dehaene et al., 1993). Crucially, however, the mapping effect did not interact with the head orientation effect, which means that both effects were unrelated. Consequently, the results account for conceptual spatial-numerical associations that can be explained with a transfer of numerical magnitude coding (maintained in working memory from the number categorization) to the tilted head trials (cf. Fischer & Shaki, 2016; Van Dijck, Abrahamse, Acar, Ketels & Fias, 2014).

3.4 Discussion of Experimental Series B

Experimental Series B investigated effects of observed vertical head orientation on numerical magnitude operations. Three experiments showed that participants produced smaller numbers in an RNG task (Experiment 1), estimated smaller quantities in an anchoring-like estimation task (Experiment 2), and chose keys associated with smaller numbers more frequently in a free choice task (Experiment 3) after they had observed a person with a head tilted down relative to a not tilted head and/or up-tilted head. This head-orientation effect was independent of the model's gaze direction, which was always directed towards the camera and, hence, oriented towards the observer. The effect was obtained with different types of numerical judgment tasks, and thus seems to be a robust phenomenon. Furthermore, head orientation influenced response choice when responses became extrinsically associated with large and small numbers through task procedures (Experiment 3), suggesting that the effect is independent of a particular response arrangement. In short, the observation of another person with her head tilted down seems to increase the accessibility of small numerical magnitudes across a broad range of tasks and situations.

3.4.1 Effects of head cueing on numerical cognition

In light of Experimental Series A, Experiments 4 to 6 indicate that the attention-orienting responses to vertical head orientations extend to numerical magnitude operations. Thus, the present findings are in line with a growing body of behavioral and neuropsychological studies showing that spatial cognition and numerical cognition interact with each other and have overlapping representations and neural substrates (for reviews see Bueti & Walsh, 2009; Hubbard et al., 2005; Walsh, 2003). Research suggests that spatial perceptions and spatial attention affect numerical cognition, and vice versa, because numbers and quantities are cognitively arranged along a mental number line: On a vertical axis from low (small numbers) to high (large numbers) and/or on a horizontal axis from the left (small magnitude) to the right (high magnitude) (Winter et al., 2015). Importantly, the influence of spatial perception on numerical cognition can also be based on social perceptions such as the perceived (dynamic) gaze shifts of another person to the bottom (left) or to the top (right) (Grade et al., 2013). Experimental Series B extends this line of research in several regards when it showed numerical magnitude effects of social perceptions of another person's (static) vertical head posture. Firstly, social effects on numerical cognitions are not exclusive to perceptions of gaze direction in close-up view. Secondly, the present research extends previous findings of social number cueing to flexible number ranges typical to anchoring and anchoring-like estimation tasks (see also Eerland et al., 2011). Thirdly, the present research substantiated that the effects of head orientation on numerical cognition are the result of a conceptual link between numbers and space and not of spatial task demands (cf. Fischer & Shaki, 2016). Finally, Experiments 4 to 6 indicated that spatial attention-orienting responses to others' visual field orientation (cf. Langton, 2000; rather than gaze direction; Hietanen, 2002; Perrett et al., 1992) extend to one's numerical space. This finding is in line with the assumed functional equivalence between numerical magnitude operations (like smaller-larger judgments) and processing within one's peripersonal space.

A critical question is what process was causally responsible for the head-orientation effect. The role of the two possible effectors (1) head tilt and (2) eye position were already discussed in the Discussion of Experimental Series A. In this context, please note that the head orientation stimuli and the number generation/estimation task in Experiments 4 and 5 were presented *sequentially* rather than simultaneously. Since the head tilt features of the pictures were more salient than the vertically shifted positions of the eyes, it seems more plausible to assume that the direction of head orientation (rather than the location of the eyes) primed the numerical magnitude operations in the following trials (via working memory; Van Dijck et al., 2014). Nonetheless, both a head cueing explanation and an eye fixation explanation rely on an attention shift in perceptual space and a sensory-motor simulation mechanism (Grade, Badets, & Pesenti, 2017; Sixtus, Fischer, & Lindemann, 2017). I will elaborate on this mechanism in more detail in the General Discussion.

A completely different, third explanation is that the position of the head changed the general appearance of the person, creating particular emotional or communicative impressions (e.g. Hehman, Leitner, & Gaertner, 2013). For instance, a person with a lowered head could have been perceived as “angry” or “depressed”. Holmes and Lourenco (2011) showed that the perceived intensity of another’s emotional facial expression ranging from mild to extreme can affect the speed of left- and right-sided responses in a SNARC-like paradigm, suggesting that magnitude information is also extracted from emotional expressions. According to this line of reasoning, however, the perception of *more* anger (depression, etc.) in displays of a lowered head should have led to *higher* numbers and estimates of magnitudes, while exactly the opposite pattern was observed in the present research. Thus, a lowered head position would have lowered the intensity of a perceived emotional expression relative to the neutral (non-tilted) head posture, which is not very plausible. In sum, an emotional appearance account cannot explain the present findings. Therefore, I will discuss the present work primarily in the context of embodied notions of spatial-numerical associations in the General Discussion.

3.4.2 Methodological considerations

The present experiments have some limitations. Firstly, only down-tilted head orientation had an effect on number processing. Presentations of up-tilted head orientation in Experiment 1 did not produce larger numbers in the Random Number Generation task. This finding indicates that magnitude information is exclusive to or more easily extracted from lowered head orientation, which is in line with research pointing to a general small number bias (e.g. Banks & Hill, 1974; Loetscher & Brugger, 2007). Moreover, this one-sided result might to reflect the presumably compressed shape of the mental number line (e.g. Dehaene & Changeux, 1993; Dehaene et al., 1993). To account for this feature of number representation, future research should use larger number ranges that extend the distance between large magnitudes. The numerical trivia questions in Experiment 5 might be a promising lead in this regard.

A second limitation is that only static displays of head postures were used in the present research. Social cueing researchers argue that when gaze and head are not congruent, observers implicitly infer motion (e.g. Pomianowska et al., 2012; see Experimental Series A). In line with this view, the present thesis assumes that the downward motion implied in the lowered head orientation influenced the observers’ attention orienting, which in turn affected numerical magnitude operations (be it generated and/or estimated numbers or judgments). Future studies might employ head movement instead of static posture stimuli to further elaborate on attention orienting as possible mechanism involved in numerical magnitude operations (see also Hubbard et al, 2005; Knops et al., 2009b).

Thirdly, it should be highlighted that the head postures were not explained to the participants and thus presented without meaningful context. It is likely that a spatial encoding of head postures is conditional and influenced by the social context in which they appear. For instance, a lowered head has a different social meaning when the person is looking down at an object at the floor compared to when she is staring at another person (as in the present studies). Effects of perceived head postures on numerical cognitions may consequently change depending on the social context in which they occur. Future studies might therefore study effects of head orientation as parts of a more complex body orientation in social situations. At this point, however, it should be noted that social stimuli are not necessary for a spatial priming of numerical magnitude operations, as many numerical cognition studies showed (for a review, see Winter et al., 2015).

Note that most behavioral studies of numerical cognition confound spatial stimuli and non-spatial responses - or vice versa (see critique of Fischer & Shaki, 2016 and Shaki & Fischer, 2018). Consequently, in these studies response priming processes underlying SNARC effects might have resulted from correspondence relations between numerical positive (large) and negative (small) as well as spatial positive (top) and negative (bottom) polarities, respectively (Proctor & Cho, 2006; Roettger & Domahs, 2015). The present experiments eliminated potential polarity correspondence artefacts by presenting the spatial cues and the numerical tasks sequentially rather than simultaneously. Additionally, the number generation and estimation tasks in Experiment 4 and 5 are less prone to spatial confound, because numerical magnitude was not unambiguously mapped onto two spatially arranged keys (and key locations were at right angles with the head orientation manipulation). Most importantly, Experiment 6 systematically disentangled the spatial arrangement of the response keys and its numerical meaning and found an effect of vertical head orientations on numerical decisions in the absence of a parallel polarity correspondence relation. Therefore, a conceptual link between numbers and space is an explanation better suited for the present results than the polarity correspondence principle. A more comprehensive discussion of explanatory accounts with regard to the assumed functional equivalence between numerical magnitude operations and peripersonal space will follow in the General Discussion

4 | General Discussion

4.1 Summary of the Empirical Part

The Experimental Series tested if observed (static and/or dynamic) vertical head cues of others affect (A) spatial attention orienting and, crucially, if this social cueing response extends to (B) numerical magnitude operations. This approach was motivated by the assumed functional equivalence between spatial processing within peripersonal space and numerical magnitude operations outlined in the Introduction. Other studies have already shown that changes in spatial attention orienting within one's own peripersonal space due to posture (e.g., canonical finger postures; Sixtus et al., 2017), movements (e.g., head movements; Winter & Matlock, 2013), or stimulation (e.g., finger stimulation; Sixtus et al., 2018b) affect numerical cognition tasks. However, the question if the same is true for the observation of others' attention orienting within their peripersonal space was scarcely addressed in numerical cognition research. Thus, the present research aimed at supporting the functional equivalence assumption by providing evidence for this chain of effects from visual perception to numerical response.

Specifically, Experiment 1 tested whether observers' attention followed gaze or head direction when viewing another person tilting her/his head from an aligned to a misaligned gaze-head posture in the vertical dimension. Therefore, participants first saw a picture of a person with a non-tilted head and gaze directed at the camera followed by a picture of the same person with an up- vs. down- tilted head while gaze was still directed at the camera. In Experiment 2, the sequence of the pictures was switched so that participants saw the tilted head pictures first followed by the non-tilted ones. In Experiment 3, participants saw tilted head pictures alone (i.e., static rather than dynamic tilted head stimuli). Please note that the target appeared within the peripersonal space of the observed person. Results indicated that participants classified targets faster that appeared in addition to the tilted head pictures and in line with head direction rather than in opposite locations (Experiments 1 and 3). By contrast, there was no head cueing effect if the head orientation shift resulted in a non-tilted head picture (Experiment 2). In terms of the two proposed functioning principles of the visual system's direction-detection mechanisms (Fig. 5), the findings are in line with an additive-contributions account (Langton, 2000) rather than gaze-primacy models (Hietanen, 2002; Perrett et al., 1992). Moreover, the results point to an attention orienting response that followed the observed person's peripersonal space representation in the vertical dimension (up- vs. down-tilted head position) rather than her/his actual focus of spatial attention (i.e., the camera and/or the participant).

Experiments 4 to 6 revealed that the attention orienting response to static tilted head pictures (like in Experiment 3) extended to a range of numerical cognition tasks. Specifically, down-tilted head stimuli primed smaller one-digit numbers in a Random Number Generation (RNG) task (Experiment 4) and smaller multi-digit estimates to numerical trivia questions (Experiment 5) relative to non- and/or up-tilted head pictures.

However, while the trivia questions in Experiment 5 provided a magnitude context for the numerical responses, the numbers' quantity code (e.g. Dehaene, 1992; Dehaene & Cohen, 1995) was irrelevant for the RNG task in Experiment 4. Experiment 6 indirectly measured the association between numerical magnitude judgments (larger vs. smaller than *5*) and attention orienting responses (upwards vs. downward). Specifically, relative magnitude associations (smaller vs. larger than *5*) learned in number trials spilled over to free key choices in tilted head picture trials. Results indicated that participants chose the key associated with large numbers more often in response to up- rather than down-tilted head stimuli - irrespective of the horizontal response key location.

To conclude, the Empirical Part of this thesis provided evidence in support of the functional equivalence of processing within peripersonal space and numerical magnitude operations. Specifically, the present work aimed at testing if other's effects on one's own near-space-processing extend to numerical cognition. Results of Experimental Series A (Experiments 1 and 3) indicated attention-orienting responses in line with others' head-centered peripersonal space representation based on response time measurements. Crucially, results of Experimental Series B showed that these attention-orienting responses to others' head orientation extended to one- and multi-digit numerical responses (Experiments 4 and 5) and smaller-larger numerical magnitude judgments (Experiment 6).

In the remainder of the General Discussion, I will at first discuss considerations across both Experimental Series A and B. The first part of these considerations are dedicated to the new look on the social cueing findings that the peripersonal space perspective allows for; the second part discusses alternatives to the suggested spatial attention-orienting mechanism in light of both Experimental Series in more detail. Then, I will spell out a process model based on a novel specification of A Theory of Magnitude (Walsh, 2003) that brings together peripersonal space processing and generalized magnitude operations. Following this analysis, I will discuss implications for numerical and other prothetic magnitude operations, on whose basis new hypotheses can be generated and further research be stimulated. Finally, I will reflect the present work in terms of numerical and embodied cognition, before I spell out possible applications.

4.2. Considerations across Experimental Series A and B

4.2.1 Observing misaligned gaze-head postures in the context of peripersonal space processing

The functional principles of peripersonal space representation, which were outlined in the Introduction, allow for taking a new look on the results of Experimental Series A and their social cueing context. In this section I will reflect on three issues pertaining to the specifics of the direction-detection mechanism responsible for the spatial attention orienting responses to observed misaligned gaze-head constellations. More precisely, I will first discuss the asymmetry between the effects of vertically and horizontally misaligned gaze-head cues. Then, I will briefly delineate why the present findings are compatible with both an observer's and an observed person's frame of reference. Finally, I will spell out the sensory-motor mirroring (or simulation) mechanism, which presumably underlies sharing peripersonal space with others, and its implications for the present work in more detail.

Firstly, the constructing principles of peripersonal space representation might reconcile the asymmetry between the spatial attention-orienting responses to viewing misaligned gaze-head constellations in the vertical vs. horizontal dimension. From a social cueing perspective (Hietanen, 1999, 2002; Langton, 2000; Perrett et al., 1992), the central finding of Experimental Series A was that attention shifts in response to up- and down-tilted heads with gaze directed at the camera (see Fig. 6) followed head orientation (Langton, 2000) rather than gaze direction (Hietanen, 2002; Perrett et al., 1992). This finding apparently contradicts the overshoot effect triggered by analogue gaze-head misalignments in the horizontal dimension (Hietanen, 1999, 2002). After all, the spatial attention shifts in response to heads turned to the left or right with gaze directed at the camera (see Fig. 4) followed gaze direction (Hietanen, 2002; Perrett et al., 1992) rather than head orientation (Langton, 2000; see Fig. 5).[19]

The supposedly conflicting result of the effects of gaze-head misalignments in the vertical (the present work) and horizontal (Hietanen, 1999, 2000) dimension might reflect an asymmetry in the processing of vertical and horizontal visual (and head-centered) peripersonal space. In line with this reasoning, a recent study on eye-head movement coordination (during visual search in a 360° visual display system; Fang et al., 2015) showed that in natural contexts, eye and head movement are usually aligned; but if direction of eye and head movement differed, the misalignment occurred more often along the vertical than the horizontal axis. Moreover, research on eye-head coordination showed that in case of saccades to targets within the ocular motor range (i.e., within head-centered peripersonal space), head movements reflected a person's expectations regarding her/his future gaze direction (i.e., are only initiated if regarded necessary following the principle of efficiency, Oommen, Smith, & Stahl, 2004). The latter finding seems superficially more in line with the present research than the overshoot effect found by Hietanen (1999, 2002). At this point, however, it is important to note the human field-of-view extends to an average angle of 200° in the horizontal dimension, but only 135° in the vertical dimension (due to the horizontal arrangement of the eyes; Werner, 1991). Additionally, the shape of the eye sockets restricts the visual field in the vertical dimension to a larger degree than in the horizontal dimension. Taken together, direction of head orientation might be a more significant indicator of one's actual (or anticipated) head-centered peripersonal space behavior in the vertical rather than the horizontal

[19] A recent study on eye-head movement coordination during visual search in a 360° visual display system (Fang et al., 2015) showed that in natural contexts, eye and head movement are usually aligned. However, if direction of eye and head movement differed the misalignment occurred more often along the vertical than the horizontal axis.

dimension. By contrast, the larger extent of the visual field in the horizontal dimension might render the information of head orientation negligible relative to that provided by gaze direction. With regard to the extent of an observed person's head-centered peripersonal space in the vertical vs. horizontal dimension, the supposedly contradicting findings might be reconcilable after all.

Consequently, the spatial attention-orienting responses of the participants in Experimental Series A and those of the participants that viewed horizontally misaligned gaze-head postures (Hietanen, 1999, 2002) might reflect the functioning principles of head-centered peripersonal space processing. Specifically, a target appearing above an up-tilted head with gaze directed at the camera might still be located within the person's visual field (i.e., head-centered peripersonal space), while a target appearing below might not (and vice versa for a misaligned down-tilted head posture). In an analogue vein, a target appearing to the right of a left-oriented head orientation with gaze directed at the camera might be located within the person's visual field, while the target appearing to the left might not. Future research might further substantiate the preference of head over gaze information when viewing misaligned gaze-head pictures in the vertical dimension (the present work) and the preference of gaze over head information in the horizontal dimension (Hietanen, 1999, 2002). In a first step, however, future studies should complement Hietanen's (1999, 2002) research by testing the influence of dynamic head movements to misaligned gaze-head postures in the horizontal dimension. After all, additional head movement information might change the interpretation of the horizontally misaligned gaze-head posture by qualifying the significance attributed to the head relative to the eyes.

Secondly, even though both the results of Experimental Series A and those of Experimental Series B lend evidence to the interpretation of the misaligned gaze-head stimuli as informative cues (e.g., Böckler et al., 2011; see also Barresi & Moore, 1996),[20] the frame of reference remains unclear. After all, the difference between the observer's and the observed person's frame of reference in the vertical (rather than the horizontal) dimension is difficult to disentangle. However, as the targets appeared within the observed person's peripersonal space, one might speculate that participants followed the observed person's head orientation in anticipation of an upcoming corresponding gaze movement to the location of the target (in terms of *implied motion*, see Pomianowska et al., 2012; see also Oommen et al., 2004). In this case, participants would interpret the cue in terms of the observed person's frame of reference. Alternatively, participants might have understood the misaligned gaze-head posture as a nonverbal communicative signal that something is approaching their own head-centered peripersonal space resulting in corresponding attention orienting responses within their own peripersonal space. In this alternative scenario, participants would interpret the cue in terms of their own frame of reference. Consequently, joint attention between observer and observed person might be

[20] Since the persons in the pictures fixate the observer at all times and irrespective of their head orientation, the direction of their respective head orientations (up- vs. down- vs. not tilted) seem to be processed as sole informative content within their postures.

established by focusing either on a location within the observer's or the observed person's peripersonal space. Based on the present work, we cannot decide between these two possibilities, especially since the distance between the participants and the Computer screen was close to the participants' own peripersonal space. With regard to peripersonal space processing, however, research points to the observed person's reference frame rather than one's own (cf. Teramoto, 2018). Please note that based on the results of the present research, either frame of reference indicates that the participants simulated the peripersonal space of the observed person (even though the pictures appeared outside their own peripersonal space). Future research might investigate the observers' attentional responses to social cueing setups in more detail, for instance by introducing a radial dimension.

Thirdly, in the literature on peripersonal space processing, the automatic extension of one's near space representation to that of someone else (without prior acquaintance (and not to a rubber hand; Teramoto, 2018) is often traced back to mirror neurons (for a study with monkeys, see Ishida et al., 2010) or neurons with mirror properties (for a recent study with human participants, see Brozzoli et al., 2013) that are presumably involved in remapping the other person's body and actions onto one's own representations.[21] On a cognitive level, simulation theories (Gallese & Goldman, 1998; Jeannerod, 2001) argue in a similar vein that perceiving others' bodily action(s) or state(s) (e.g., tilted head postures) is simulated in one's own motor system (a process called "covert action") for the purposes of understanding, interacting, and copying. In terms of the *Theory of Event Codes* (Hommel et al., 2001), such a direct link between sensory input (perception) and (to-be-produced) motor output (actions) in the brain is based in a common representational medium (called *Event Codes*) for their respective sensory-motor features (called *Feature Codes*). In line with this view, both the perception of related features (e.g., vertical space) and action directed towards these features (e.g., spatial attention shift, head movement) should be facilitated in response to perceiving the head orientation stimuli employed in the present work (Hommel et al., 2001). In light of such simulation and common coding accounts, however, the spatial attention-orienting as common underlying mechanism of both Experimental Series A and of Experimental Series B might be reinterpreted as mere proxy of a more basic sensory-motor mechanism. I will elaborate further on such a low-level link between peripersonal space and magnitude-numerical associations in time (see also Walsh, 2013). First, let me address alternative explanations across both Experimental Series A and B in the next section.

In sum, the functional principles of peripersonal space representation have implications for the interpretation of the results of Experimental Series A and their social cueing context. Firstly, the differences between the spatial attention-orienting responses

[21] For instance, a recent study (Brozzoli et al., 2013) identified neuronal populations in the premotor cortex than encode both one's hand-centered peripersonal space and that of someone else. Moreover, one of the Experiments by Teramoto (2018) demonstrated that hand-centered peripersonal space was not extended to a rubber hand, indicating a human bias of the proposed underlying mirror mechanism.

to vertically (Experimental Series A) and horizontally misaligned gaze-head misalignments (Hietanen, 1999, 2000) might be traced back to deviating construction principles of head-centered peripersonal space representation for the vertical and horizontal dimension. After all, the visual field extends father into horizontal than vertical space, which might render the head a more informative cue of one's vertical rather than head-centered peripersonal space representation. Secondly, Experimental Series A does not inform us about the frame of reference (egocentric vs. altercentric) that the participants take when processing the peripersonal space of someone else. The found spatial attention-orienting responses in the vertical dimension are compatible with both an observer's and an observed person's frame of reference. Finally, the cognitive manifestations of the mirror mechanism typically recruited to explain extensions of peripersonal space representation to others allow for a reinterpretation of the spatial attention-orienting mechanism attributed to both Experimental Series A and B.

4.2.2 Discussion of alternatives to a visuospatial attention-orienting mechanism

The present work interprets the results of Experimental Series A and B in support of a link between visuospatial attention orienting and numerical magnitude operations within a shared peripersonal space representation context. In this context, Experimental Series B extended and conceptually replicated the gaze cueing effects on random number generation demonstrated by Grade and colleagues (2013), who used shifting eye stimuli in close-up view. Moreover, Experiments 4 to 6 complement research that showed effects in the opposite direction, namely numerical magnitude effects on visuospatial attention orienting (e.g., Fischer et al., 2003; Sixtus, Lonnemann, Fischer, & Werner, 2019). Nonetheless, several processes or combination of processes might be involved in the congruency effects between head orientation, spatial attention orienting, and numerical magnitude processing. In this section, I will first briefly discuss alternative processing accounts based on an emotional and social interpretation of the tilted head postures. Secondly, I will elaborate on the explanatory value of more high-level embodied cognition accounts like cognitive metaphor theory (e.g., Lakoff & Johnson, 1980)

Firstly, at least some of the present findings could be interpreted in terms of changes in the general emotional or social appearance of the observed persons due to their head posture. As I had already discussed in the Empirical Part, one study associated the perceived intensity of an observed person's facial expression to numerical magnitude (Holmes & Lourenco, 2011). However, in a recent rating study (Hehman et al., 2013), both the up- and down-tilted head pictures were perceived as more extreme in terms of their emotional expression relative to the non-tilted head pictures. Therefore, both up- and down-tilted heads should have been associated with larger numerical magnitude. Since the results of Experimental Series B contradict this prediction, an explanation based on the emotional intensity of the observed person's facial expressions offers no plausible alternative to the suggested spatial attention-orienting mechanism. In a similar vein, an embodied cognition account that associates vertical space with social power perception might argue that the up-tilted head pictures indicate "superiority" and the down-tilted head pictures "inferiority" (Schubert, 2005). In consequence, a mechanism following the polarity correspondence principle (Proctor & Cho, 2006) might be responsible for the results of Experimental Series B, which associates "superior" to "larger" and "inferior"" to "smaller". A second look, however, reveals that such a polarity correspondence account based on power perception is incompatible with at least the one-tailed effects in Experiment 4 and hence not suitable to account for the present findings. In addition to these conclusions, neither accounts based on emotional perceptions, social power perceptions, nor polarity perceptions can parsimoniously account for the results of Experimental Series A. After all, participants did not classify the location of the target (above vs. below), but its shape (circle vs. square) employing counterbalanced response keys (between subjects), which means that there was no systematic semantical or polarity association between head orientation stimuli and the employed response codes. In sum, an explanation based on visuospatial attention orienting in both perceptual and numerical space (e.g., Grade et al., 2013) seems to offer a more parsimonious explanation across Experiments 1 to 6 than alternative accounts based on emotional or social perceptions of the tilted head pictures.

Secondly, cognitive metaphor theory (e.g., Lakoff & Johnson, 1980) offers a relatively high-level explanation that might account for part of the results of the present work. This language-based theory suggest that abstract concepts like numerical magnitude were metaphorically mapped to concrete domains like vertical space (Lakoff & Johnson, 1980).[22] In a similar vein, some embodied cognition authors (e.g., Barsalou & Wiemer-Hastings, 2005) stressed the significance of the concrete situational contexts of the acquisition of an abstract concept like number for its mental simulation. Therefore, given the numerical context of the studies in Experimental Series B, the up- and down-tilted head orientations might have been interpreted as "more" or "less" rather than affecting numerical magnitude operations (or even symbol classifications) via a low-level spatial attention-orienting mechanism. Such a high-level interpretation might indeed account for the numerical estimation results in the context of trivia question context in Experiment 5 and the key choices in the context of the magnitude judgments in Experiment 6. However, it offers neither a parsimonious explanation for the one-tailed effects in Experiment 4, nor a plausible interpretation of the response time results of Experimental Series A. [23]

In sum, neither accounts based on emotional or social perceptions with regard to the tilted head pictures nor metaphor theory (or similar situated cognition accounts) offer a comprehensive and parsimonious explanation for the results of both Experimental Series

[22] For instance, vertical metaphors are often used in everyday language to describe magnitudes as in "more is up" (Fischer & Brugger, 2011) or "prices are high" (Johnson, 1987; Lakoff & Nuñez, 2000; Pecher & Boot, 2011)

[23] Please note that some authors (e.g., Walsh, 2013) do not necessarily see a conflict between metaphorical accounts and low-level embodied cognition accounts like the Theory of Magnitude (Walsh, 2003). After all, they address different levels of analysis as the latter aims at pre-linguistic and motoric processes.

A and B. Consequently, low-level spatial attention-orienting in both peripersonal space and its numerical magnitude manifestation seem the best explanation to account for the results of the present work.

4.3 Involvement of Peripersonal Space Processing in Generalized Magnitude Operations: A novel specification of A Theory of Magnitude

In line with other authors (e.g., Longo & Lourenco, 2010), the present thesis proposed that numerical magnitude operations share functional features with processing within peripersonal space, in particular plurimodal spatial attention orienting. This novel proposition was traced back to the origins of both near space representation (e.g., Cléry et al., 2015; Holmes & Spence, 2004) and number processing (e.g., Walsh, 2013) in perception and action. More precisely, however, A Theory of Magnitude (Walsh, 2003) postulated that not only number and quantity, but *all* prothetic (i.e., magnitude domains than can be experienced that can be experienced as “less than” or “more than”; cf. Stevens, 1957) magnitude processing originated in the manipulation of objects via reaching and grasping (Walsh, 2013). Consequently, I propose that the plurimodal spatial attention-orienting mechanism shared by number operations and peripersonal space processing extends to a more comprehensive magnitude operating system. In this chapter, I will first discuss the present work in terms of the Theory of Magnitude (ATOM; Walsh, 2003, 2013). In this context, I will propose a novel specification of its Generalized Magnitude System in terms of the functional features of processing within peripersonal space. In the second section, I will discuss implications of a functional equivalence between generalized magnitude operations and peripersonal space processing in light of past and future research.

4.3.1 The present research in the context of A Theory of Magnitude (ATOM): A process model

The Theory of Magnitude (Walsh, 2003, 2013) proposed that numbers are but one manifestation of analogue magnitude and that the latter shared an underlying generalized mechanism with other *prothetic* dimensions like space, time, and quantity. More precisely, Walsh (2013) postulated that all these magnitude dimensions “share[d] the same basic spatiotemporal metrics upon which numerical understanding is built” (p. 2). Clearly, the present work and the extended functional equivalence assumption point to spatial attention orienting as one mechanism underlying numerical magnitude operations (i.e., smaller-larger judgments). Given that the present work is in line with the Theory of Magnitude (Walsh, 2003, 2013), the question arises which role peripersonal space processing might play for generalized magnitude operations. In the following, I will first reflect the results of Experimental Series B in terms of a Theory of Magnitude (Walsh, 2003). In this context, I will outline a process model of magnitude operations. Finally, I will argue that the functional properties shared by the Generalized Magnitude System and peripersonal space extend to plurimodal spatial attention-orienting.

Following Walsh (2013), the effects of observed spatial codes on numbers in Experiments 4 to 6 are the high-level result of a low-level, pre-linguistic generalized magnitude processing system that is mediating between perception and numbers for the purpose of action (cf. Hommel, 2015; Hommel et al., 2001). In line with Walsh (2013), I speak of "perception" and "action" instead of "space" as numerical cognition and development can be conceptualized in terms of their sensory-motor origins in action and sensory integration. More specifically, Walsh (2003, 2013) tried to trace the Generalized Magnitude System's location in the parietal lobe back to its origins in motoric interactions with the environment.[24] He suggested that the encoding of magnitude information in the external world for the purpose of action is the function that links the parietal lobe's various capacities. To put it differently, he reinterpreted the function of the parietal cortex from computing the location of objects in space (i.e., where) to computing magnitude information of objects (i.e., how far, fast, much, long, and many) for the purpose of bodily responses and actions (Walsh, 2003). In this view, the head orientation effects in Experiments 4 to 6 seem perfectly in line with the action-based approach of A Theory of Magnitude (Walsh, 2003, 2013).

In spite of its merits, the Theory of Magnitude (Walsh, 2003, 2013) did not address the question *how* analogue magnitude is operated along the shared "basic spatiotemporal metrics" (p. 2), which presumably precede symbolic number output (in terms of the Triple Code Model, Dehaene, 1992; Dehaene & Cohen, 1995). To close this gap, I propose that a spatial attention orienting mechanism underlies the results of both Experimental Series A and B and that the former provides an answer as to the operating question. Specifically, I argue that processing within peripersonal space and operating magnitude are functionally equivalent. In favor of this argument, a recent review of the Theory of Magnitude (Walsh, 2013) predicted that all magnitude systems should respond differently to stimuli within near space (i.e., peripersonal space) and those outside (i.e., in extrapersonal space) as a function of distance between actor and object. However, Walsh (2013) restricted the proposed overlap in terms of functional properties with peripersonal space to the distance-aspect of action space – a position the present thesis challenges.

[24] In a book chapter, Walsh (2013) posited that at the bottom of his theory was the question *why* the parietal cortex is built as it is rather than *how* magnitude cognition works. The parietal cortex had been associated with automatic and motoric processing (Freund, 2001; Pisella et al., 2000) rather than abstract and higher level processes, which had been associated with temporal regions (e.g. language, episodic memory, and object recognition; see Nobre & Mccarthy, 1995; Schacter & Wagner, 1999; Eichenbaum, Yonelinas, & Ranganath, 2007, respectively). Nonetheless, numbers, time and space were associated with regions within the parietal lobe (e.g., intraparietal sulcus; Walsh, 2013). Following Cajal's (1898/1999) claim that all configurations in nature are functional, he inferred anatomical overlap or functional equivalence from their shared location (Walsh, 2003).

With regard of the present research, I present a process model of magnitude perception in terms of A Theory of Magnitude, which might look like Figure 19. Here, sensory-motor simulation is employed to determine magnitude in the external world for the purpose of a behavioral response (Walsh, 2003, 2013), be it an action, a spatial attention response, or a numerical symbol (spoken or written; Dehaene, 1992). In this context, spatial attention orienting is one of the pivotal processes for sensory-motor computations of how far, how fast, how much, how long, and how many regarding one's actions in near space (di Pellegrino & Làdavas, 2015). Crucially, literature on peripersonal space construction stresses its multisensory nature and identifies not only vision, but also touch, audition, and proprioception as decisive modalities (e.g., Farnè & Làdavas, 2002; Holmes & Spence, 2004).[25] In this vein, it is important to note that embodied cognition accounts (Wilson, 2002) and the Theory of Event Codes (Hommel, 2015) suggest that internalized sensory-motor interactions with the environment can be simulated off-line, i.e. without actually showing overt action or even activating the associated motor patterns. With regard to the present research, this means that the actual presence of perceivable magnitudes is not necessary for the outlined process model. Therefore, the results of Experiments 4 and 5 could be interpreted in terms of an off-line spatial simulation of magnitude that was translated into a numerical symbol response (in terms of the Triple Code Model; Dehaene, 1992). In this context, the effect of the head orientation stimuli can be reinterpreted in terms of an interference of the observed person's head direction (i.e., head-centered peripersonal space) with the low-level basis of the number generation (Experiment 4) and numerical estimation generation (Experiment 5) processes. In a similar vein, the results of Experiment 6 should be understood as a conceptual correspondence effect between the low-level spatial head direction code and the respective magnitude code (cf. Fischer & Shaki, 2016). Nonetheless, based on the possibility of mere preparation of a spatial attention-orienting response (in terms of the Theory of Event Codes; Hommel, 2015) rather than an embodied simulation or actual shift (e.g., Wilson, 2002), the suggested mechanism might be a mere proxy of a more basic sensory-motor mechanism (for an effect of spatial coordination on numerical estimates without an attention involvement, see Eerland et al., 2011).

[25] Please note that in this context, the term 'attention' is employed to describe processes "that give rise to a temporary change (often enhancement) in signal processing" (Spence, 2010).

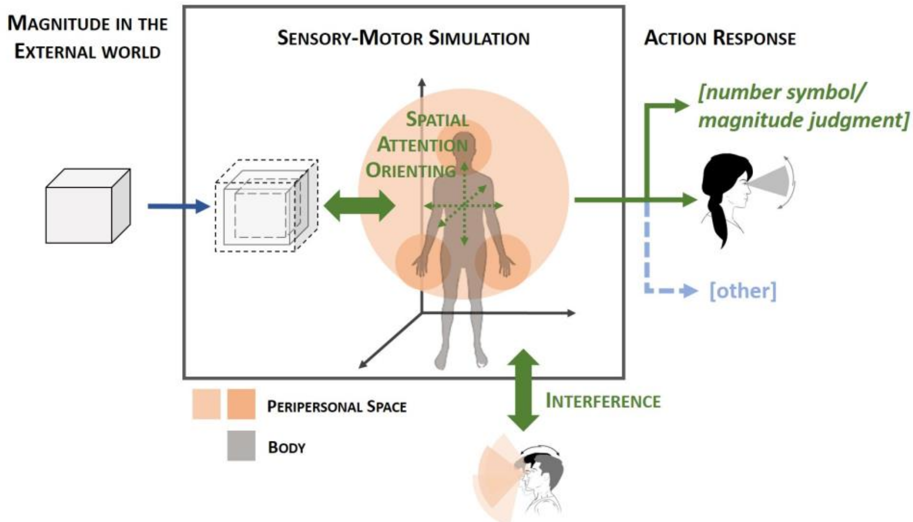

Figure 19. The figure shows a process model of magnitude perception (indicated by the cubicle to the right) and processing (center) in terms of A Theory of Magnitude (Walsh, 2003, 2013). The frame separates the external world from internal sensory processing, integration, matching/scaling, and high-level cognition (as far as cognition is necessary; Walsh, 2013). In this context, the present thesis suggests that plurimodal spatial attention orienting (*green*) within peripersonal space plays a significant role in computing the *HOW*s (how far, how fast, how much, how long, and how many) of magnitude for the purpose of action (left). If the response is a bodily action (e.g., spatial attention shift), no high-level mediator is necessary (Hommel et al., 2001). If the response is a number symbol or magnitude judgment (such as in Experiments 4 to 6), working memory is the best candidate for an intermediary entity (van Dijck & Fias, 2011). Please note that according to this process model, the effects of Experiments 4 to 6 could be explained with interference of another person's head-centered peripersonal space (indicated by the person below the frame).

Beyond the scope of the present work, I suggest spatial attention orienting (due to its role within peripersonal space processing) to be involved in - if not pivotal to many of - the underlying processes that are shared across prothetic dimensions in terms of the Generalized Magnitude System (see Fig. 19). This novel specification is compatible with the general characteristics defined in A Theory of Magnitude (Walsh, 2003, 2013): (1) Spatial attention orienting can map "less than" or "more than" extents of magnitude. (2) Overlapping activation has been reported for visuospatial attention orienting and numerical (Knops et al., 2009b) and other magnitude operations (e.g., Pinel, Piazza, Le Bihan, & Dehaene, 2004).[26] Additionally, shifts in visual, tactile, and auditory spatial attention were associated with the parietal lobe (for visuotactile near space, see Holmes & Spence, 2004; for auditory near space, see Farnè & Làdavas, 2002), which constitutes

[26] Empirical support for the proposed functional equivalence could also be deduced from the cerebral proximity of numerical magnitude and peripersonal space processing. After all, neuropsychological research indicated that the parietal lobe was associated with both magnitude (e.g., number, space, luminance; see Pinel et al., 2004) and peripersonal space representations (Duhamel, Bremmer, Hamed, & Graf, 1997; for a review, see Hubbard et al., 2005). For instance, the ventral intraparietal area of the intraparietal sulcus was suggested to play a role in constructing the multisensory representation of space close to the head (cf. di Pellegrino & Làdavas, 2015). In numerical cognition research, neurons from the very same area were shown to code for numerosity and space (Tudusciuc & Nieder, 2009).

preliminary evidence in line with Walsh's (2003) cerebral proximity reasoning. (3) Spatial attention orienting is not identical with an already existing prothetic dimension but constitutes a processing mechanism for action and perception in space. Moreover, this feature of peripersonal space processing offers a plausible and parsimonious explanation for results beyond the present work, including many of the behavioral numerical cognition studies that were based on spatial perception (e.g. Grade et al., 2013) or action (e.g. Winter & Matlock, 2013). In fact, the present work deduced the involvement of spatial attention orienting (due to its role in peripersonal space processing) from its functional role for action coordination in the external world (e.g. di Pellegrino & Làdavas, 2015) rather than on the basis of cerebral proximity (Walsh, 2003, 2013). In a sense, one might argue that the suggested specification puts Walsh's (2003, 2013) Generalized Magnitude System "from the head onto its feet".

In sum, the results of Experimental Series B are in line with the notion of a Generalized Magnitude System based on sensory-motor interactions with the external world (Walsh, 2003). Moreover, the plurimodal spatial attention-orienting mechanism proposed for numerical magnitude operations in the present work adds a novel specification to the process model outlined in terms of A Theory of Magnitude (Walsh, 2003, 2013). Therefore, I suggest functional equivalence of generalized magnitude operations and processing within peripersonal space extends to plurimodal spatial attention orienting (in contrast to Walsh, 2013). In consequence, spatial attention shifts should be involved in many operations with(in) prothetic magnitude manifestations. Its implications will be discussed and elaborated in the next section, where I will touch on some predictions to be tested in future experiments.

4.3.2 Implications of an involvement of peripersonal space processing in generalized magnitude operations

An involvement of processing within peripersonal space in magnitude operations across prothetic dimensions has several implications for future research. First, I will discuss what follows from the proposed generalization of a plurimodal spatial attention-orienting mechanism for magnitude operation across prothetic dimensions. In this context, I will outline limitations of the proposed mechanism in terms of the spatial limits of peripersonal space representation and the peculiarity of the different prothetic dimensions. Then, I will outline features of peripersonal space with regard to action and perception (hand- and head-centered, modalities, modifications) in the context of their significance for future research on prothetic magnitude operations. Finally, I will briefly address some limitations in terms of previous propositions of A Theory of Magnitude (Walsh, 2003, 2013).

If spatial attention orienting is pivotally involved in the Generalized Magnitude System (Walsh, 2003, 2013), interference effects of spatial cues (in different modalities) should not be restricted to numbers but extend to magnitude operations along other prothetic dimensions. In a similar vein, spatial attention-orienting shifts should play a mediating role when prothetic dimensions interfere with each other. Preliminary evidence in line with these hypotheses comes from a study that indicated both partial brain activity overlap (in the parietal lobe) and similar cost and benefit effects for spatial and temporal attention allocation in a behavioral experiment (Coull & Nobre, 1998). Moreover, participants responded faster to darker color (or darker shades of the same color in) with a response key to their left, and faster to a brighter color (or brighter shades of the same color) with a response key to their left (Fumarola, Prpic, Da Pos, Murgia, Umiltà, & Agostini, 2014). Another study showed interference effects of magnitude dimensions associated with spatial attention like numerosity and size, on temporal judgments (Xuan, Zhang, He, & Chen, 2007). One study showed that an explicit mapping of musical pitch to space via training improved the estimation of musical intervals of non-musicians (Loudwin & Bannert, 2017), even though Walsh (2013) explicitly excluded pitch from the dimensions processed by the Generalized Magnitude System. More cross-prothetic magnitude effects were shown for numerical magnitude on time perception (e.g., Kiesel & Viereck, 2009) and luminance level (Cohen Kadosh, Cohen Kadosh, & Henik, 2008). Since numerical magnitude was shown to affect visuospatial attention behavior (e.g., Fernández, Rahona, Hervás, Vázquez, & Ulrich, 2011), one might speculate about a role of spatial attention orienting in the latter experiments. In fact, however, studies are necessary that do not only hint at the involvement of a spatial attention-orienting mechanism, but explicitly test for it via interference manipulations or additional measurements (e.g., eye-tracking for vision).

Please note that the hypothesis that spatial attention orienting is involved in magnitude operations along prothetic dimensions implies two practical qualifications. Firstly, the suggested spatial attention-orienting mechanism should be limited to magnitude processing within reaching distance (Chen et al., 2015; Walsh, 2013). Indeed, both peripersonal space (Li et al., 2011) and numerical cognition research (Longo & Lourenco, 2010) showed visuospatial processing differences between information from near and far space. More precisely, the former experiment (Li et al., 2011) indicated a modulation of the contributions from different visual pathways in dependence of distance, while the latter (Longo and Lourenco, 2010) showed a common rightward bias (i.e., spatial sifts to the right and larger numbers) [27] of attention in perceptual and numerical space. Future research should test if analogue common modulations in dependence of distance can be found in other prothetic dimensions like time, luminance, and pitch. Secondly, I do not expect effects within or between other prothetic dimensions to be identical to those in Experiments 4 to 6, because not all prothetic dimensions are created equal (even though they share processes and overlapping activations; cf. Walsh, 2013). For instance, numbers were shown to interfere with time, but not the other way round (Brown, 1997). Walsh (2013) speculated that language acquisition might be involved in such differences between magnitude domains.

[27] You find a more detailed description of the experiment in the Introduction of this thesis.

If the Generalized Magnitude System (Walsh, 2003) and processing within peripersonal space representation are functionally equivalent, the latter's features with regard to action and perception, other people, and tool use should extend to prothetic magnitude operations. Firstly, representations of space were suggested to be centered on action-relevant body parts, in particular head and hands (e.g., Làdavas, di Pellegrino, Farnè, & Zeloni, 1998a; see Fig. 2). After all, these more fine-grained representations within peripersonal space are pivotal in guiding motor behavior for the purpose of interacting with objects in the environment (di Pellegrino & Làdavas, 2015). Indeed, the majority of numerical studies seem to reflect this accentuated role of hand- (e.g., effect of numerical magnitude on the speed of grip aperture; Lindemann, Abolafia, Girardi, & Bekkering, 2007) or head-centered peripersonal space (e.g., the present work; Longo & Lourenco, 2010; Winter & Matlock, 2013). Moreover, one study showed an interference effect of numerical magnitude on the estimation of object graspability (Badets, Andres, Di Luca, & Pesenti, 2007), reflecting the nature of near space as "multisensory-motor representation of the body in space" (Pellencin et al., 2018, p. 164). Future studies should test for interference effects of other prothetic magnitudes on hand- and head-centered measures or, vice versa, of perceptual cues addressing these two peripersonal space spheres on magnitude-related responses (e.g., response times or estimation tasks).

Secondly, all modalities relevant for action are presumably involved in the construction of peripersonal space, which is why neuropsychological evidence showed strong cross-modal links between vision, touch, proprioception, and audition (see di Pellegrino & Làdavas, 2015; Driver & Spence, 1998; Holmes & Spence, 2004; Làdavas, 2002). [28] In line with such cross-modal links, one study explicitly interpreted its interference effects of numerical magnitude on tactile stimulus detection in terms of cross-modal effects from vision to touch (Brozzoli et al., 2008). With regard to the action-relevant modalities, however, a majority of numerical cognition tasks can be clustered into only three groups, namely of touch (e.g., Sixtus et al., 2018b), proprioception (e.g., Hartmann et al., 2012), and vision (e.g., Grade et al., 2013). By contrast, auditory stimuli were rarely pursued in numerical cognition research (e.g., Piazza, Mechelli, Price, & Butterworth, 2006), not to mention other prothetic dimensions (Loudwin & Bannert,

[28] Nonetheless, various lines of research showed that the visual modality often dominates the others (e.g., Posner, Nissen, & Klein, 1976). For instance, participants often ignore auditory stimuli when presented together with visual targets (Colavita effect; Colavita, 1974), perceive a completely different third sound when they view a person speak one sound while listening to another one (McGurk effect; McGurk & MacDonald, 1976), and integrate a rubber hand in their body schema based on visual training and perception alone (rubber hand illusion; Botvinick & Cohen, 1998; Ehrsson, Spence, & Passingham, 2004).[28] Nonetheless, the auditory modality was shown to dominate vision in a number of tasks (e.g., Shams, Kamitani, & Shimojo, 2000). Therefore, Spence (2010) suggested visual dominance in spatial contexts and auditory dominance in temporal task.

2017).[29] Therefore, future research might not only transfer methods from numerical cognition research to other prothetic magnitude dimensions, but investigate the effects of auditory stimuli on numerical magnitude tasks.

Thirdly and crucially with regard to the present work, research indicated that one's representation of peripersonal space is modulated by the presence of others (either restricted, e.g. Driver & Spence, 1998, or extended, e.g. Teramoto, 2018). In fact, the present research can be understood in terms of a simulation of the observed person's head-centered peripersonal (and numerical) space. Future research should attempt to conceptually replicate the present findings with other prothetic magnitude domains. In this vein, tool use was also shown to increase the extent of hand-centered visual peripersonal space along the tool axis (Farnè & Làdavas, 2000). Therefore, tools might be a promising alternative to humans in testing the effects of hand-centered extensions of peripersonal space on the processing of magnitude.

Finally, the spatial attention-orienting specification of generalized magnitude operations has its limitations and seems to contradict earlier accounts in several aspect. Firstly, Walsh (2003) explicitly denied that attentional processes could add any explanatory value to the investigation of the mechanisms underlying magnitude processing. According to him, attention has too many incarnations and is a parameter too non-specific and malleable to shed light on the Generalized Magnitude System. Therefore, it is important to note that the present suggestion restricts itself to the spatial orienting aspect of attention. More precisely, it follows the definition used in the literature on peripersonal space processing, which understands spatial attention-orienting as processes "that give rise to a temporary change (often enhancement) in signal processing" (Spence, 2010). Moreover, the present thesis does not postulate that spatial attention orienting is the only mechanism shared across prothetic magnitude dimensions.

In sum, functional equivalence between peripersonal space processing and analogue magnitude operations (in terms of the Generalized Magnitude System; Walsh, 2003, 2013) has several implications for future research. For instance, spatial attention orienting should affect the processing of prothetic magnitude and vice versa, even though this link should be limited to near space and need not be symmetric for all magnitude dimensions. Moreover, features of peripersonal space representations regarding action and perception should extend to operating prothetic dimensions: (1) The accentuated role of the regions surrounding hands and head should be reflected in magnitude processing. (2) All modalities relevant for the spatial aspects of action and perception (vision, touch, proprioception, audition, and their interactions) should interfere with magnitude operations and vice versa. (3) Modifications via the presence of others or tool

[29] Please note that researchers are still debating if cross-modal effects are the result of direct cross-modal links or of multisensory integration (cf. Spence, 2010). While these two processes were long regarded as closely related (Stein, Wallace, & Meredith, 1995), some authors regard them as rather separate processes that only partially overlap in their neural architectures (Bolognini, Frassinetti, Serino, & Làdavas, 2005; Spence & Santangelo, 2009).

use should interfere with magnitude processing. Beyond these implications for future research, the present research contradicts an earlier proposition of A Theory of Magnitude (Walsh, 2003) that *attention* cannot add any explanatory value to the question what mechanism underlie magnitude processing. After all, at least the facet of *attention* that is relevant for locating events within one's peripersonal space (and involved in coordinating actions on them) seems to add some elucidation to this discussion.

4.4 The present work in the context of magnitude perception and representation

In this chapter, I will reflect on the present work and the extended peripersonal space approach to prothetic magnitude processing in terms of a broader numerical cognition and embodied cognition perspective. First, I will discuss if and to what extend the proposed accentuated role of plurimodal spatial attention orienting is in line with the properties associated with the notion of a *number sense* (Dehaene, 2011, Feigenson et al., 2004). Then, I will briefly discuss the features of the head cueing effects on number processing (Experimental Series B) in terms of a hierarchical system of tropic (sometimes also labeled "grounded"), embodied, and situated cognition (TEST theory; Myachykov et al., 2014; see also Fischer, 2012).

In the Introduction, I started with the notion of a *number sense* that grasps the abilities from perception of quantities to mentally operating numerosities (Dehaene, 2011; Feigenson et al. 2004) and helps with recognizing changes in a number of objects immediately (Dantzig, 1967/2007; Dehaene, 2011). [30] This supposedly automatic and innate numerosity mechanism was suggested to be subdivided into two core systems (Feigenson et al., 2004; cf. Dehaene, 2011): One for the precise representation of small numerosities up to 4 (called *subitizing*; Kaufman et al., 1949); the other for the approximate representation of larger numerosities and numbers (called *Approximate Number System*; Feigenson et al., 2004). These core systems were both assumed to work cross-modal and to be found across species (i.e., among both humans and animals; cf. Leibovich, Katzin, Harel, & Henik, 2017), which is line with the proposed role of peripersonal space processing. In addition, several authors found evidence suggesting that *subitizing* was based on a fast object tracking mechanism relying largely on visual input and the visuospatial working memory (e.g., Piazza, Fumarola, Chinello, & Melcher,

[30] The idea of a more general *sense of magnitude* (e.g., Meck & Church 1983; Moyer & Landauer 1967) rather than restricted to numerosity alone has recently found renewed interest, in numerical and mathematical cognition literature (Henik, Gliksman, Kallai, & Leibovich, 2017; Leibovich & Henik, 2013; Leibovich et al., 2017). In line with the idea of a Generalized Magnitude System (Walsh, 2003, 2013), this notion proposes a holistic process that considers and weights all available sensory magnitude information rather than extracting numerosity information alone (Gevers, Cohen Kadosh, & Gebuis, 2016; Gebuis, Cohen Kadosh, & Gevers, 2016). Consequently, some authors posit that humans and animals alike are not born with the ability to represent numerosities, but to distinguish continuous magnitudes automatically (Leibovich & Henik, 2013).

2011). Hence, spatial attention orienting seems to be the decisive mechanism underlying subitizing. Moreover, the *approximate number system* was associated with a computational model based on the spatial locations of the objects alone (ignoring other sensory or motor information like color; Dehaene & Changeux, 1993). Thus, plurimodal spatial attention orienting as feature of peripersonal space processing seems to be involved in (if not pivotal for) both systems proposed to be in charge of non-symbolic numerosity perception (Feigenson et al., 2004).

Grounded and embodied cognition accounts (Wilson, 2002; Barsalou, 2008) posit that all semantic concepts are grounded in sensory-motor representations, i.e. they are linked to perceptual and motor codes (e.g., Fischer & Zwaan, 2008; Glenberg & Kaschak, 2002).[31] Specifically, they assume that features of the environment (e.g., effects of gravity), the body (e.g., motor program involved in a head shift), and/or the situation (e.g., conditioning) become part of cognitive representations in long-term memory via repeated co-occurrence. In this context, the relative stability of representational features such as the associations between numbers and spatial directionality (Winter et al., 2015) was suggested to depend on their respective origins in either the environment, the body, or the situation (Myachykov et al., 2014; see also Fischer, 2012; Fischer & Brugger, 2011). Thus, the hierarchical system of tropic (sometimes also labeled “grounded”), embodied, and situated cognition (TEST theory; Myachykov et al., 2014; see also Fischer, 2012) allows for a classification of representational features in terms of their malleability to training. With regard to this hierarchical embodied cognition framework, the head cueing effects on numerical processing outlined in the present thesis constitute an interesting case, because features from all three levels were involved.

The head orientation stimuli employed in the present work are cases of situated cognition, as they situationally activate embodied head orientation simulations that were formed based on tropic verticality experiences with magnitude in the external world. More precisely, the vertically oriented mental number line that the present work is based on reflects the vertical accumulation (i.e., piling up) of objects and quantities in the physical environment (i.e., magnitude; Myachykov et al., 2014; cf. Fischer, 2012). Therefore, the vertical feature of number representation is labeled *tropic* in terms of the stability hierarchy, which means that it counts among the most stable and automated representational features. By contrast, embodied features of conceptual representations encoded the cognizer’s bodily state during acquisition. Regarding the present work, up-tilted head orientation should be associated with “more” in terms of magnitude as one looks up to larger accumulations of objects (see also Fischer & Brugger, 2011; Lakoff & Núñez, 2000), while down-tilted head orientation should be associated with “less” following the same logic. The crucial differences to tropic features are that embodied features of numbers need to be learned via repeated association to magnitudes, code not only shared bodily features but also individual ones (like handedness; see body-

[31] In fact, several authors suggested knowledge representation to be abstract and isolatedly stored relative to body experiences and/or properties (e.g., Mandl & Spada, 1988).

specificity hypothesis, Casasanto, 2009; see also Casasanto & Henetz, 2012)[32], and are essential for simulation. Finally, situated features of conceptual representations are flexible as they recruit tropic and/or embodied associations depending on which features the cognizer attends to due to the situational context. In the present research, the situational features were the stimuli that activated different embodied spatial codes (in the tropic vertical dimension) on a trial-by-trial basis.

To conclude, an involvement of peripersonal space processing and spatial attention orienting in numerical magnitude operations is compatible with the functional features associated with an innate *number sense* (Feigenson et al., 2004). Moreover, while Experimental Series B addressed all levels of the hierarchical system of tropic (i.e., association of numbers to vertical space), embodied (i.e., simulation of the observed head orientation), and situated cognition (i.e., the use of different head orientation stimuli), the underlying spatial attention-orienting mechanism links magnitude operations across prothetic dimensions first and foremost to the body (Myachykov et al., 2014). Since the embodied level within the proposed hierarchy allows for training and simulation (Myachykov et al., 2014), the link between magnitude operations and peripersonal space processing might be a promising lead for applications such as in math education programs. In the final chapter, I will briefly elaborate on how the present work and the link between magnitude operations and peripersonal space processing might be applied in the classroom and beyond.

4.5 Application in the classroom and beyond

For a long time considered a problem in developmental and educational psychology (cf. Bryant & Squires, 2001), the results of numerical cognition research suggested that mapping numbers onto space can actually be regarded as a resource for the development of mathematical understanding in children. For instance, children's spatial skills were shown to be associated with their success in math (e.g. Casey, Nuttall, Pezaris, & Benbow, 1995). This link was attributed to the role of spatial skills in creating a linear number line representation, which in turn presumably helps with arithmetic estimation (Gunderson, Ramirez, Beilock, & Levine, 2012). In line with this view, the accuracy of a children's mental number line was indeed shown to predict their success in learning the correct solutions of both familiar and unfamiliar arithmetic tasks (Booth & Siegler, 2008). Moreover, bodily moderators between space and numbers like finger gnosis (i.e., the abilities to distinguish between fingers, name and indicate them; Reeve & Humberstone, 2011) were shown to predict early counting skills and calculating/quantity comprehension (Poltz, Wyschkon, Höse, von Aster, & Esser, 2015). Even in adults, finger

[32] For instance, SNARC research showed that not all participants show spatial-numerical associations in line with a horizontal mental number line. Some participants even show a reversed pattern (e.g., Shaki & Fischer, 2008), which can be attributed to individual differences in terms of learning history or handedness (Casasanto & Henetz, 2012).

counting habits were shown to be part of associations between numbers and horizontal space (Fischer, 2008).

Several educational programs already aimed at materializing the spatial grounding of numerical magnitude. For instance, space-based material like empty number lines (e.g. Blöte, Van der Burg, & Klein, 2001) and linear number board games (Siegler & Ramani, 2009; Ramani & Siegler, 2011) were already employed when teaching (symbolic) number-quantity associations (e.g. magnitude comparison, numeral identification) and basic arithmetic skills (addition, subtraction). However, several embodied methods that were based on the sensory-motor basis of quantity were shown to excel in comparison with more classical teaching approaches (Link, Moeller, Huber, Fischer, & Nuerk, 2013; Fischer et al., 2011; Link, Schwarz, Huber, Fischer, Nuerk, Cress, & Moeller, 2014). For instance, one training taught first-graders to map numerical magnitude onto space by walking to locations along a mental number line (Link et al., 2013). In another training, kindergarten children learned spatial-magnitude associations by responding in a magnitude comparison task via steps on different fields of a dance mat (Fischer et al., 2011). The latter training was even successfully adapted for the teaching of two-digit numbers in second-graders (Link et al., 2014).

In the context of embodied teaching programs, the present work has implications for how students might be taught associations between number symbols and non-symbolic quantity in pre- and elementary school. In light of its link to magnitude operations, future education programs might consider employing children's individual and shared peripersonal space to teach them number-quantity associations. For instance, future teaching programs might develop and test a joint number symbol location task, in which one child locates numbers along a vertical line while the other child is allowed to help her/him to find the correct position via vertical spatial cues (like head nods, eye movements, finger pointing, or a combination). Thus, children learn to associate smaller-larger judgments and distance with the orienting of attention in space, which might support the development of the accuracy of both children's number line representations. Furthermore, teachers might consider using the vertical rather than the horizontal number line when demonstrating the location of number symbols. After all, vertical space was shown to be spontaneously associated with numerical magnitude (in contrast to horizontal space; Sixtus et al., 2019) and does not afford that children incorporate the teachers' perspective.

Apart from mathematical education, peripersonal space processing and its social facet might be applied in other (prothetic) magnitude contexts in the classroom and beyond. For instance, a recent study showed that associating pitch with space improves the estimation of musical intervals (Loudwin & Bannert, 2017). Therefore, singing teachers and choir leaders might develop, train, and employ more fine-grained spatial cueing strategies to lead their students or singers during performance. Moreover, any kind of negotiation pertaining to numerical content such as in the price of something, one's salary, or the evaluation points one gets at work should be carried out with the body heading for the desired direction. In sum, the results of the present research might be applicable in essentially any situation, in which one aims at cueing a larger or smaller magnitude nonverbally to another person - even if the magnitude at hand might just reflect an estimate for the number of jewels in a showcase.

4.6 Conclusion

The scope of the present thesis was to test the social implications of the assumed functional equivalence of numerical magnitude operations (e.g., smaller-larger judgments) and peripersonal space processing (i.e., multisensory-motor representation of space in reaching distance). In support of this hypothesis, the present research showed that the effects of observing social displays such as the ostensive vertical orientation of someone else's head are not restricted to visuospatial attention shifts (Experimental Series A). Instead, spatial attention-orienting responses were shown to extend to concurrent or subsequent numerical magnitude operations, supposedly based on the association of numbers and space (Experimental Series B). In this vein, the present experiments integrated theory and research of numerical cognition, social cueing, and peripersonal space research. Beyond the empirical scope, an involvement of peripersonal space processing in general and spatial attention orienting in particular in operating magnitude across prothetic dimensions was discussed in terms of a Generalized Magnitude System (Walsh, 2003, 2013).

The present work has several implications for Numerical, Embodied, and Social Cognition research should take into account. Firstly, the situational features of the employed social spatial stimuli might inspire future studies in both numerical and other prothetic magnitude contexts such as quantity, time, luminance, or musical pitch. Secondly, future research might test the plurimodal nature of the suggested spatial attention-orienting mechanism (i.e., vision, touch, and audition) across prothetic magnitude dimensions. Thirdly, Social Cognition researchers might be interested in investigating which implications and limitations follow from peripersonal space representation for the effects of social cueing. Fourthly, participants in Experimental Series A and B seem to have involuntarily followed the cues of other people in both spatial and numerical dimensions, even though they had no information about those people. These results of can be interpreted in terms of a human propensity to joint attention if not shared intentionality, which are important components of a supposedly unique human ability: intentional cooperation towards joint goals (Tomasello, Carpenter, Call, Behne, & Moll, 2005; p. 675). Thus, educational programs in early math or music classes might profit from taking into account both individual and shared peripersonal space representation from both a numerical cognition and a social cognition point of view.

Finally, Walsh (2013) postulated that at some point one framework will describe both sensory and magnitude processing across research fields that have been considered separately for now. Specifically, he envisioned one general explanation from sensory development through cross-modal interactions to expressions of the modalities in higher cognition, be it magnitude in general or numbers in particular. The way towards such a unified theory of sensory-motor cognition might still be long. In this context, however, the novel association of magnitude operations with peripersonal space processing might turn out to be a promising step into the direction of such an overarching endeavor.

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Appendix A: Data availability

All pictures used in Experiments 1-6, the trivia questions employed in Experiment 5, as well as all the datasets generated and analyzed in the course of the present thesis are available in the following Open Science Framework repositories:

Experimental Series A

https://osf.io/8vmzh/?view_only=cc17ab2f2aa240bb98c36804bae0b7cb

Experimental Series B

https://osf.io/rtkdp/?view_only=9bc2382dd85946fc8cd5f8a86d4a8125

Appendix B: Deutschsprachige Zusammenfassung

In vielen Teilen der modernen Welt werden Zahlen als Werkzeuge verwendet, um räumliche Zusammenhänge zu beschreiben - seien es Höhen, Breiten oder Entfernungen. Die Verbindung geht jedoch tiefer, denn eine Vielzahl von Studien hat gezeigt, dass Zahlen räumlich in der Vertikalen (bzw. Horizontalen) verankert sind. So können Zahlen die räumliche Wahrnehmung und umgekehrt Wahrnehmungen oder Bewegungen im Raum die Größe von Zahlenschätzungen beeinflussen. Diese Verbindung findet mittlerweile sogar didaktische Anwendung in der Vermittlung von Zahlenbedeutung bei Kindern. Allerdings wissen wir noch wenig über die kognitiven (und neuropsychologischen) Prozesse, die konkreten Zahlengrößenoperationen (d.h. Größer-Kleiner-Urteile, Addition, etc.) zugrunde liegen.

Mehrere Autoren deuteten an, dass die Verarbeitung innerhalb des körpernahen Raumes (d.h. des Raumes in Handlungsreichweite) und das Operieren mit Zahlengrößen funktional äquivalent sind. Diese Annahme hat mehrere Implikationen, die die vorliegende Arbeit beschreiben möchte. So spielt die die visuell-sensorische Modalität eine hervorgehobene Rolle bei Verarbeitung wie Orientierung innerhalb des körpernahen Raumes. In der Tat legen neuropsychologische und behaviorale Studien eine ähnliche Rolle des Sehens und insbesondere der visuospatialen Orientierung auch für Zahlengrößenoperationen nahe. Darüber hinaus zeigte die soziale Kognitionsforschung, dass sich Bewegungen, Posen und Gesten nicht nur auf die Repräsentation des eigenen körpernahen Raumes, sondern auch auf das visuospatiale Orientierungsverhalten eines Beobachters auswirken. Vor diesem Hintergrund wird in der vorliegenden Arbeit die spezifische Implikation der funktionalen Äquivalenz getestet, dass sich die visuospatiale Orientierungsreaktion auf die Pose einer beobachteten Person auch auf die Zahlengrößenoperationen des Beobachters erstreckt.

Der empirische Teil der vorliegenden Arbeit testet die räumliche Orientierungsreaktion von Beobachtern auf Kopfneigungen in der Vertikalen (bei Augenkontakt zum Beobachter) im wahrgenommenen ebenso wie numerischen Raum. Im Rahmen dieser Untersuchung werden zwei Experimentalreihen vorgestellt, die beide Teilschritte umfassen: Von der Beobachtung der vertikalen Kopfposition (trotz auf die Augen ausgerichteter Blickrichtung) einer anderen Person zur gerichteten Aufmerksamkeitsreaktion beim Beobachter (Experimentalreihe A); sowie von dieser Orientierungsreaktion auf die beobachtete Person zu Größenoperationen mit Zahlen beim Beobachter (Experimentalreihe B). Es zeigte sich, dass die Beobachtung einer Bewegung von einer neutralen Ausgangsposition zu einer vertikalen Kopfposition (Experiment 1) ebenso wie die einer vertikalen Kopfpose alleine (Experiment 3) die räumliche Aufmerksamkeit eines Beobachters in Übereinstimmung mit der beobachteten Kopforientierungsinformation (nach oben vs. unten) verschob. Eine Bewegung von einer vertikalen zu einer neutralen Endposition hingegen zeigte keinen Effekt auf die räumliche Orientierung des Beobachters (Experiment 2). Desweiteren generierten Beobachter bei nach unten geneigten Kopfposen (relativ zu nach oben bzw. nicht geneigten Kopfposen) kleinere Zahlen in einer Zufallszahlengenerierungsaufgabe (zwischen 1 und 9; Experiment 4), gaben kleinere Schätzungen auf numerische Allgemeinwissensfragen ab (überwiegend mehrstellige Zahlen; Experiment 5) und wählten in einem Doppelbelegungsparadigma weniger häufiger diejenige von zwei Antworttasten, die sie in einer alternierend zu bearbeitenden Größenaufgabe für größere Zahlen verwenden sollten.

Die Ergebnisse der Experimentalreihe A zeigen, dass die Betrachtung der Kopforientierung einer anderen Person im Beobachter tatsächlich die erwartete gerichtete Aufmerksamkeitsreaktion auslöste. Basierend auf dieser Vorarbeit stützen die Ergebnisse der Experimentalreihe B die Annahme, dass Zahlengrößenoperationen in der visuospatialen Verarbeitung des körpernahen Raumes verankert sind. Damit brachten die vorliegenden Studien Forschung zu numerischer und sozialer Kognition ebenso sowie zur peripersonalen Raumverarbeitung zusammen. Darüber hinaus legt der empirische Teil der vorliegenden Arbeit die Grundlage, um eine mögliche Rolle von Verarbeitung innerhalb des peripersonalem Raumes im Kontext der Größentheorie von Walsh (2003, 2013) auszuarbeiten. In diesem Zusammenhang wird die Größentheorie in einem handlungsbasierten Verarbeitungsmodell spezifiziert, das die zentrale Rolle der räumlichen Aufmerksamkeitsorientierung betont. Implikationen für die Forschung zur mentalen Verarbeitung von Größen und Anwendungsmöglichkeiten im Klassenzimmer sowie darüber hinaus werden diskutiert.

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