Adults' spatial scaling from memory: Comparing the visual and haptic domain

Magdalena Szubielska*, [1], Marta Szewczyk[1] and Wenke Möhring[2, 3]

Author Note

* **Corresponding author:** Magdalena Szubielska, magdasz@kul.pl

[1] Institute of Psychology, The John Paul II Catholic University of Lublin, Al. Racławickie 14, 20-950 Lublin, Poland

[2] Department of Educational and Health Psychology, University of Education Schwäbisch Gmünd, Oberbettringer Strasse 200, 73525 Schwäbisch Gmünd, Germany

[3] Faculty of Psychology, University of Basel, Missionsstrasse 60/62, 4055 Basel, Switzerland

Abstract: The current study compared adults' spatial scaling from memory in the visual and haptic domain. Adults (*N* = 32, aged 19–27 years) were presented with a spatial-scaling task in a visual condition as well as a haptic condition (in which participants were blindfolded throughout the experimental session). In both conditions, they were presented with an embossed graphic including a target (i.e., a map). Then, they were asked to encode this map and to place a disc at the same spot on an empty referent space from memory. Maps had three different sizes whereas the referent space had a constant size, resulting in three different scaling factors (1:1, 1:2, 1:4). Participants' response times and absolute errors were measured. Order of perceptual condition was counterbalanced across participants. Analyses indicated that response times and absolute errors increased linearly with higher scaling factors in the visual as well as the haptic perceptual condition. In analogy to mental imagery research, these results suggest the usage of mental transformation strategies for spatial scaling.

Keywords: spatial scaling; spatial cognition; haptic cognition; visual cognition

Adults' spatial scaling from memory: Comparing the visual and haptic domain

Introduction

Spatial scaling is defined as being able to relate spatial information in different-sized spaces (Frick & Newcombe, 2012). This ability is an important aspect of spatial cognition and is involved in several situations that we are confronted with in daily life. For instance, we use this ability when relating distances provided in a map to the distances in the large-scale environment that we are moving in. Furthermore, we use spatial scaling when relating information between a small-scaled model (e.g., in architecture, museums, etc.) to the information of the real-word referent object. In addition to its importance in common activities, spatial scaling was also specified as an overarching theme for science, technology, engineering, and mathematics (STEM) disciplines by the National Research Council of the United States (2012). In line with this claim, studies demonstrated that spatial scaling ability is an integral part when reasoning about proportions (Boyer & Levine, 2012) and is related to an understanding of mathematics, chemistry, and biology (e.g., Frick, 2019, Hodgkiss et al., 2018; Möhring et al., 2015, 2018; for a training study, cf. Gilligan et al., 2019).

The majority of previous research on spatial scaling investigated this ability in the visual domain (e.g., Frick & Newcombe, 2012; Hund et al., 2020; Huttenlocher et al., 1999; Möhring et al., 2014, 2018; Plumert et al., 2019; Vasilyeva & Huttenlocher, 2004). A typical procedure in these studies was that participants were presented with a map showing a target and an empty referent space (i.e., map-reading tasks or localization paradigms). Then, they were asked to use the information provided in the map in order to place a target in the referent space. Importantly, sizes between the maps and the referent space varied systematically, with the goal to create different scaling factors and ultimately, to investigate participants' ability to scale distance information.

But how do we solve such spatial scaling tasks? Several studies have identified three different strategies (for an overview, Gilligan et al., 2018; Möhring et al., 2016). Using an "absolute" spatial scaling strategy, individuals encode the target location provided in a map in an absolute way and match the identical information onto a given referent space, regardless of differences in scale. This strategy works well when relating spaces that are quite similar in size. However, with increasing size difference between the spaces (i.e., with higher scaling factors), errors increase linearly while response times may not differ between scaling factors. The second "relative distance" strategy involves a proportional encoding of spatial information. In this strategy, individuals encode relative distances of the target and surrounding objects such as the borders of a space (i.e., a target being in the middle between two borders or being one-quarter from the right border). An identical relative distance is afterwards mapped onto the referent space (Huttenlocher et al., 1999; Uttal et al., 2006). Such a strategy works as accurately and quickly regardless of whether the map and the referent space may differ in size. In other words, participants' errors and response times are expected to remain constant across different scaling factors. A third "mental transformation" strategy refers to the usage of mental zooming. Such a mental transformation process was shown in studies investigating mental rotation, mental scanning, or object matching (Bundesen & Larsen, 1975; Kosslyn, 1975; Larsen & Bundesen, 1978; Shepard & Metzler, 1971). Similar to these mental imagery processes, participants may use mental imagery when scaling spatial information. That is, they encode the spatial location of the target in the map and may mentally transform the size of the image when performing the spatial scaling task. Following empirical evidence from mental imagery research (e.g., Kosslyn, 1975; Shepard & Metzler, 1971), this mental zooming may elicit more errors and higher response times with larger transformations. Therefore, errors and response times are expected to increase linearly with higher scaling factors.

As can be seen in this description of different scaling strategies and their effects on participants' responses, several methodological constraints have to be met in order to disentangle these strategies. One crucial precondition refers to systematically varying scaling factors. Another important precondition refers to assessing participants' errors as well as response times given that strategies are associated with a differential pattern of these dependent variables (cf. Gilligan et al., 2018). To date, only few studies have met these methodological requirements. The majority of previous research has typically measured accuracy but not response times (e.g., in Frick & Newcombe, 2012; Hund et al., 2020; Möhring et al., 2018; Plumert et al., 2019; Szubielska et al., 2019, 2021). Other studies have only tested a single scaling factor in a within-subject design (e.g., in Plumert et al., 2019; Siegel et al., 1979), making it difficult to study systematic changes in participants' performance as a function of scaling factor. When focusing on studies that did meet these methodological considerations, we can see that a) these studies are rare as of today and b) revealed heterogeneous findings (Gilligan et al., 2018; Möhring et al., 2014; 2016). Two of these studies suggested a mental transformation strategy when scaling spatial information (Möhring et al., 2014; 2016) while one study indicated a relative distance strategy (Gilligan et al., 2018). However, these studies varied widely with respect to the methodology (using map-reading vs. discrimination paradigms) and the investigated age groups (ranging from 4-year-old children to adults), making comparisons rather challenging. For example, within the map-reading tasks (localisation paradigm), participants are asked to indicate the corresponding position of a target in an empty referent space. Responses are then typically coded as deviation from the correct answer. Within a discrimination paradigm (as used in Gilligan et al., 2018; Möhring et al., 2016), participants are asked to decide whether a referent space including a target is a scaled version of a map with a target, and responses are typically encoded as correct vs. incorrect. Given the mixed findings in previous research, in the current study, we aimed to further increase our understanding of strategy use in adults' spatial scaling. In contrast to previous literature, we used a novel approach that addressed the above-mentioned methodological constraints (i.e., by varying scaling factors systematically and by measuring response times and accuracy).

As a second goal of the current study, we aimed to compare spatial scaling between the visual and haptic domain. This goal was based on the rationale that spatial information is not only encoded via the visual sense but also via the haptic sense. Perceiving objects by touch provides multi-facetted spatial information about an object's size, orientation, and it's relation to surrounding objects. Studies examining adults' recognition of maps or objects showed various similarities between performance in the visual and haptic modality (Craddock & Lawson, 2009a, 2009b; Giudice et al., 2011; Srinivas et al., 1997), suggesting that spatial scaling may not differ between the visual and haptic modality. For example, participants' response times and errors were comparable across both modalities (Giudice et al., 2011) and equally affected by size changes of the objects (Craddock & Lawson, 2009a, 2009b; Giudice et al., 2011). Indeed, some researchers have proposed a functional equivalence of spatial representations in the haptic and visual domain (Giudice et al., 2011; Loomis et al., 2013; Ottink et al., 2021) and that spatial information is encoded independently of modality in the human brain (e.g., Bryant, 1997; Huffman & Ekstrom, 2019; Levine & Schwarzbach, 2018; Wolbers et al., 2011).

Even though previous studies have already investigated effects of size changes on participants' accuracy in haptic object recognition (Craddock & Lawson 2009a, 2009b; Srinivas et al., 1997; Szubielska, 2015; Szubielska & Bałaj, 2018; Szubielska et al., 2019; 2021), these studies do not allow conclusions with respect to spatial scaling strategies. As is the case in the visual domain, these studies have often not varied scaling factors systematically (e.g., Craddock & Lawson 2009a, 2009b; Srinivas et al., 1997; Szubielska,

2015) or did not measure errors *and* response times (Szubielska et al., 2019, 2021). Two studies that met these constraints in the haptic domain were conducted by Szubielska and Möhring (2019; 2022). In the first of these respective studies (Szubielska & Möhring, 2019), adults were presented with the map and the referent space simultaneously as was typically done in previous scaling studies in the visual domain (e.g., Frick & Newcombe, 2012; Möhring et al., 2014, 2018). While this approach worked well in the visual domain, it showed some disadvantages in the haptic domain. As haptic perception is a sequential process (see e.g., Lederman & Klatzky, 2009), exploring the map by touch took longer for larger maps as compared to smaller maps. Consequently, participants' exploration times interfered with the time used for scaling spatial information, making it difficult to rely on response times as an indicator for scaling *per se* (for a detailed discussion, see Szubielska & Möhring, 2019). In a subsequent study (Szubielska & Möhring, 2022), the authors used a three-step approach: participants were asked to a) learn about a map, b) imagine the map at a given scale, and c) indicate the target location on the referent space from memory. Response times were assessed while participants were asked to imagine the map. Using this kind of approach allowed to separate the exploration process from indicating the target in the referent space. However, as participants were explicitly asked to imagine the maps on a given scale, they may have been encouraged to use mental transformation strategies.

Building on this previous research, in the present study, we used a two-step approach that similarly enabled disentangling response times and errors (for similar procedures, see Plumert et al., 2019; Szubielska et al., 2021), but did not prompt participants to imagine the learned map. More concrete, the experimental task consisted of subsequent stages of a) learning the map and b) giving a response in an empty referent space (with an assessment of errors and response times at this latter stage). Using this approach, we aimed at comparing spatial scaling in the visual and the haptic domain and importantly, aimed at assessing scaling strategies in both domains.

The present study

In the current study, we evaluated whether different perceptual conditions (visual vs. haptic) modulate the usage of spatial scaling strategies. To this end, participants performed either a spatial localization task in a visual condition or a haptic condition (by blindfolding participants). Size difference between the map and the referent space were manipulated systematically, creating three different scaling factors (1:4, 1:2, 1:1). Crucially, we addressed methodological constraints of previous research by separating the phase of perceiving the map and giving a response, and measured response times and errors. We predicted that participants may use mental transformation strategies when scaling maps in the visual and the haptic domain based on findings suggesting functional equivalence of spatial representations in the haptic and visual domain (Giudice et al., 2011; Loomis et al., 2013; Ottink et al., 2021) and a modality-independent coding of spatial information in the human brain (e.g., Bryant, 1997; Huffman & Ekstrom, 2019; Levine & Schwarzbach, 2018; Wolbers et al., 2011). Furthermore, this kind of strategy can be expected given results of previous spatial scaling studies in the visual domain (Möhring et al., 2014; 2016) and haptic domain (Szubielska & Möhring, 2022).

Method

Participants.

Thirty-two young adults aged between 19 and 27 years (M_{age} = 22.41, SD_{age} = 2.13, 16 females) participated in the present study[1]. Three of them were left-handed. Most of the participants were psychology students (n = 17). The other participants were students from a variety of degree programs. All participants had normal or corrected-to-normal vision and were compensated with 50 PLN (approx. 11 Euro) for their participation.The current experiment was conducted in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards and was approved by the [BLINDED FOR REVIEW]. Written informed consent was obtained from all participants prior to data collection.

Materials and Design.

We used 22 boards (148.5 mm high x 210.0 mm wide) with embossed graphics which were made of cardboard (for analogous stimuli, see Szubielska & Möhring, 2019; Szubielska et al., 2019; 2021) and a 1-cm large disc that participants used to respond. One of these boards represented the referent space. This referent space was indicated by a convex rectangular shape centered on the board. The size of this referent space was constant across the experiment (110.0 mm high x 170.0 mm wide). Additionally, there were 21 boards representing the maps. In analogy to the referent space, their size was indicated by a convex rectangular shape centered on the board. By contrast to the referent space, maps were smaller and included a convex spherical target at one of seven different locations. The sizes of the maps corresponded to three different scaling factors (1:4, 1:2, 1:1). Therefore, maps ranged from 27.5 mm x 42.5 mm (equivalent to scaling factor: 1:4), to 55.0 mm x 85.0 mm (scaling

---

[1] A priori power analyses using G-Power 3.1 revealed that 28 participants would be needed in order to detect a within-participant effect in a repeated measure analysis of variance (ANOVA), based on a moderate effect size of f = .25 (cf. findings from Szubielska & Möhring, 2019), significance levels of p < .05, and a power of .80. We decided to test 4 more participants to increase the number of participants to n = 16 in each condition (haptic condition first vs. visual condition first). Overall, it seems that our analyses are adequately powered.

factor: 1:2), and to 110.0 mm x 170.0 mm (scaling factor: 1:1). The diameter of the targets ranged accordingly from 2.5 mm (scaling factor: 1:4), to 5 mm (scaling factor: 1:2), and to 10 mm (scaling factor: 1:1). Additional boards presenting three maps and the referent space were used in practice trials (see Figure 1), which we used for ensuring that participants understood the instructions.

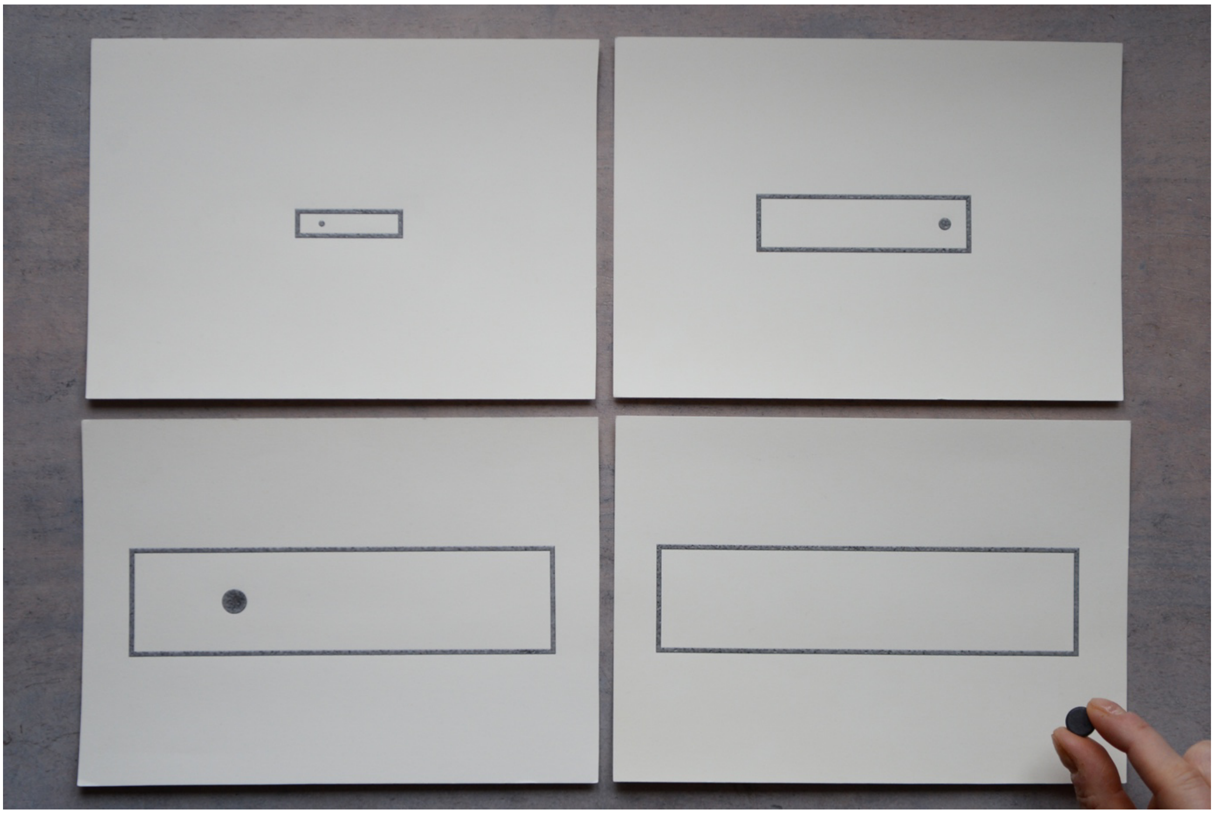

Figure 1. Boards and a disc used in practice trials.

Procedure.

Participants were tested individually in a single session lasting approximately 45 minutes. During the experiment, participants sat at a table and boards were placed subsequently on the table in front of the participant. One experimenter sat next to the left side of the participant and a second experimenter stood to the right side of the participant. Each participant completed the scaling task in two perceptual conditions: visual and haptic. The order of the perceptual conditions was counterbalanced across participants (as well as across both genders). In the visual condition, participants were allowed to view the boards but not allowed to touch them. In the haptic condition, participants were blindfolded prior to the start of the task and got acquainted with the boards by touch. In each condition, the same seven target locations were used for each scaling factor (for x- and y-coordinates, cf. Appendix), amounting to a total of 21 maps for each perceptual condition (total of experiment: 42 trials). Trials were presented in a random order in each perceptual condition.

The procedure of the spatial scaling task in each perceptual condition began with practice trials in which the experimenter explained the task. In these practice trials, participants were presented with maps in three sizes. Each participant's task was to encode the target on the map and then to place a disc at the same location on the referent space. Each trial consisted of two stages (for a similar procedure, see e.g., Szubielska et al., 2021): (1) perceiving and learning the map and its target and (2) indicating the same location on the empty referent space from memory.

During the first stage, participants were asked to encode the target's location without a time restriction. One experimenter was concerned with measuring each participant's learning times. In the visual condition, participants were instructed to only open their eyes upon the experimenter's signal and to close their eyes as a sign that they had memorized the target's location. Learning time was measured from the moment the map was placed on the table and participants opened their eyes until the moment when participants closed their eyes. In the haptic condition, participants were instructed to only touch the board upon the experimenter's signal and to stop touching the maps as a sign that they had memorized the target's location. Learning time in the haptic condition was measured from the moment participants touched the board until the moment when participants stopped touching the boards.

During the second stage in each condition, participants were presented with the referent space and asked to place a disc at the same location of the target. Response times of this stage were measured similarly to the learning times, from the “start” signal given by the experimenter to the “ready” signal provided by the participant. The two experimenters worked concurrently to ensure a smooth procedure. One of the experimenters was concerned with placing the boards in front of the participant, giving signals, and measuring the learning as well as response times. The other experimenter was concerned with measuring the coordinates of the disc placed on the referent space.

Coding.

In spatial scaling research, each answer from participants can be coded for multiple types of errors, based on the x- and y-coordinates and using different formulas. In the current study, we were interested in reversal errors, absolute errors, and signed errors (both horizontal and vertical ones) and explain each type and interpretation below.

Reversal errors. It is possible that participants produce reversal errors, in which they indicated targets on the wrong side of the space (left vs. right; up vs. down). Recent research indicated that children are prone to this kind of error (e.g., Frick & Newcombe, 2012; Huttenlocher et al., 1994; Plumert et al., 2019) and even adults commit this kind of error from time to time (Szubielska et al., 2019). To investigate whether these reversal errors would differ between the two perceptual conditions, we checked our data for reversal errors on the horizontal and vertical dimension following common approaches of these previous studies. To identify horizontal reversal errors (i.e., responses where the disc was placed on the wrong side of the referent space), we checked whether answers were on the right side of the board (i.e., x-coordinate of the response > 85 mm) for targets initially presented on the left side from the midpoint and vice versa. Then, we calculated the number of these errors in each scaling factor (for similar procedures, cf. Frick & Newcombe, 2012; Möhring et al., 2014; Plumert et al., 2019; Szubielska & Möhring, 2019; Szubielska et al., 2019). Moreover, we coded vertical reversal errors, by identifying responses that were located on the upper side of the referent space (i.e., y-coordinate of the response > 55 mm) for targets initially presented below the midpoint and vice versa. Again, we calculated the number of these errors in each scaling factor.

Absolute errors. Absolute errors reflect the distance between a participant's answer and the correct target location and were calculated based on the x- and y-coordinates using a formula for the length of a segment in a plane.

Signed errors. In addition, we investigated adults' directional, signed errors. Signed errors give insight into the direction of participants' localization errors and elucidate potential underyling biases (e.g., responding towards the midpoint or the borders of a space). When coding horizontal signed errors, we subtracted the x-coordinate of the respective target location from the x-coordinate of each participant's answer (in mm, for similar procedures, cf. Frick & Newcombe, 2012; Szubielska & Möhring, 2019; Szubielska et al., 2019; 2021). Negative signed errors indicate answers located too far to the left on the referent space; positive signed errors indicate answers located too far to the right on the referent space. Vertical signed errors were calculated by subtracting the y-coordinate of the respective target location from the y-coordinate of each participant's answer. These errors were then collapsed for top locations (targets L1, L3, and R2), as well as for bottom locations (targets L2, R3, R1; cf. Appendix). Negative signed errors indicate answers located too far to the bottom on the referent space; positive signed errors indicate answers located too far to the top on the referent space.

Outliers. We identified outliers in participants' response times and errors (mean + 3 *SD*s). Outliers were found in 1.49% of all cases (i.e., 1344 answers) for participants' response times, in 1.86% for learning times, in 1.86% for absolute errors, in 1.86% for horizontal signed errors, and in 1.41% for vertical signed errors. We excluded these outliers and collapsed data across all trials of each participant to yield an indicator of spatial scaling performance.

Results

Descriptive statistics on the reversal errors, absolute errors, learning times, and response times are presented in Table 1. Scatter plots showing x- and y-coordinates of participants' answers for each scaling factor and both perceptual conditions are presented in Figure 2. The datasets generated and analyzed during the current study are available in the Figshare repository (https://doi.org/10.6084/m9.figshare.19217016.v1).

Reversal errors.

When inspecting the averaged reversal errors as provided in Table 1, it can be seen that adults committed reversal errors on very few occasions and then placed the disc on the wrong side of the space. Given that reversal errors happened rarely, we refrained from including inferential statistics. However, from a descriptive perspective, it seems that reversal errors happened very seldomly in the visual condition, whereas the frequency seemed to be slightly higher in the haptic condition. In addition, when taking the order of perceptual conditions into account, it seems that participants who conducted the haptic condition first showed larger reversal errors as opposed to participants who conducted the visual condition first.

Table 1

The number of horizontal and vertical reversal errors, mean absolute errors (in mm), as well as learning times (in s) and response times (in s) as a function of scaling factor (1:4, 1:2, 1:1), presented for each perceptual condition (visual and haptic), separately for each order of the perceptual condition (haptic first vs. visual first). Standard deviations are presented in parentheses.

Dependent variables	**Order of perceptual condition**	**Perceptual condition**					
		Visual			**Haptic**		
		Scaling Factor					
		1:4	**1:2**	**1:1**	**1:4**	**1:2**	**1:1**
Horizontal Reversal Errors (#)	Visual first ($n = 16$)	0.00 (0.00)	0.00 (0.00)	0.06 (0.25)	0.06 (0.25)	0.06 (0.25)	0.06 (0.25)
	Haptic first ($n = 16$)	0.06 (0.25)	0.06 (0.25)	0.00 (0.00)	1.06 (1.43)	0.37 (1.02)	0.13 (0.50)
Vertical Reversal Errors (#)	Visual first ($n = 16$)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.25 (0.45)	0.13 (0.34)
	Haptic first ($n = 16$)	0.00 (0.00)	0.00 (0.00)	0.06 (0.25)	0.06 (0.25)	0.44 (0.63)	0.50 (0.73)
Absolute Errors (in mm)	Visual first ($n = 16$)	9.84 (3.03)	8.23 (2.73)	7.17 (2.12)	14.06 (5.49)	13.37 (3.68)	12.00 (3.92)
	Haptic first ($n = 16$)	10.50 (5.12)	10.33 (5.12)	6.45 (1.73)	22.30 (8.97)	19.10 (5.31)	13.60 (4.09)
Learning Times (in s)	Visual first ($n = 16$)	3.75 (2.70)	3.90 (2.94)	3.96 (3.38)	13.52 (6.18)	15.17 (6.15)	17.45 (7.71)
	Haptic first ($n = 16$)	4.44 (3.34)	4.77 (3.49)	5.18 (4.04)	13.06 (7.32)	13.72 (7.98)	15.00 (8.08)
Response Times (in s)	Visual first ($n = 16$)	5.11 (2.85)	5.18 (2.98)	4.79 (2.71)	13.71 (5.70)	13.97 (5.72)	12.77 (4.85)
	Haptic first ($n = 16$)	6.21 (3.24)	5.94 (2.76)	5.96 (2.76)	13.41 (6.23)	12.77 (6.20)	12.55 (5.52)

Absolute errors.

To investigate whether participants' absolute errors differed as a function of the perceptual conditions, we computed an analysis of variance (ANOVA) with participants' absolute errors as dependent variable, scaling factor (1:1 vs. 1:2 vs. 1:4) and perceptual condition (visual vs. haptic) as within-participant variables and order of perceptual condition (haptic first vs. visual first) as a between-participants variable. In case of violations of the sphericity assumption, we used the Greenhouse-Geiser-corrected values in this and the following analyses. This ANOVA showed a significant effect of perceptual condition (see Table 2 for inferential statistics). Follow-up comparison (with Bonferroni adjustments here and throughout) yielded that participants produced more errors in the haptic condition (M = 15.74, SE = 0.67) than in the visual condition (M = 8.75, SE = 0.55; $p < .001$). The analysis revealed also a significant effect of scaling factor, which was best described by a linear function, $F(1, 30) = 20.42$, $p < .001$, $\eta_P^2 = .41$. Participants produced larger absolute errors with increasing scaling factor ($M_{1:4} = 14.18$, $SE_{1:4} = 0.94$ vs. $M_{1:2} = 12.76$, $SE_{1:2} = 0.56$ vs. $M_{1:1} = 9.81$, $SE_{1:1} = 0.41$). The interaction effect between scaling factor and perceptual condition was not significant.[2] Therefore, it seems that errors increased linearly with higher scaling factor in participants of both perceptual conditions.

In addition, there was a significant effect of order of perceptual condition, which was qualified by a significant interaction between perceptual condition and order of perceptual condition. Post-hoc comparisons revealed that participants in the haptic condition produced significantly higher absolute errors when being first presented with the haptic condition as opposed to being first presented with the visual condition ($M_{\text{haptic first}} = 18.33$, $SE_{\text{haptic first}} = .95$

---

[2] Naturally, absolute errors are largely affected from participants' reversal errors which indicate large deviations from the correct target location (by responding on the incorrect side of the field). Similar to research with children and adults (Huttenlocher et al., 1994; Möhring et al., 2014), we gave adults credit and folded their response distributions in the middle and by doing so, accounted for such reversal errors. When computing analyses with these absolute errors that were corrected for reversal errors, it was found that the pattern of results remained unchanged. Thus, it seems that the number of reversal errors has not influenced our results.

vs. $M_{\text{visual first}} = 13.15$, $SE_{\text{visual first}} = .96$, $p < .001$). Similar comparisons for participants in the visual condition yielded non-significant effects. There was also a significant interaction between scaling factor and order of perceptual condition. Post-hoc analyses showed that participants from the group presented first with the haptic condition produced more errors in case of scaling factor 1:4 and 1:2 (both *p*s < .001).

Overall, the analyses with participants' absolute errors revealed that participants produced larger absolute errors in the haptic as opposed to the visual condition. These larger errors occured predominantly when being presented with the haptic condition first. Importantly, our findings indicated that absolute errors increased linearly with higher scaling factors which was found for the visual as well as the haptic perceptual condition.

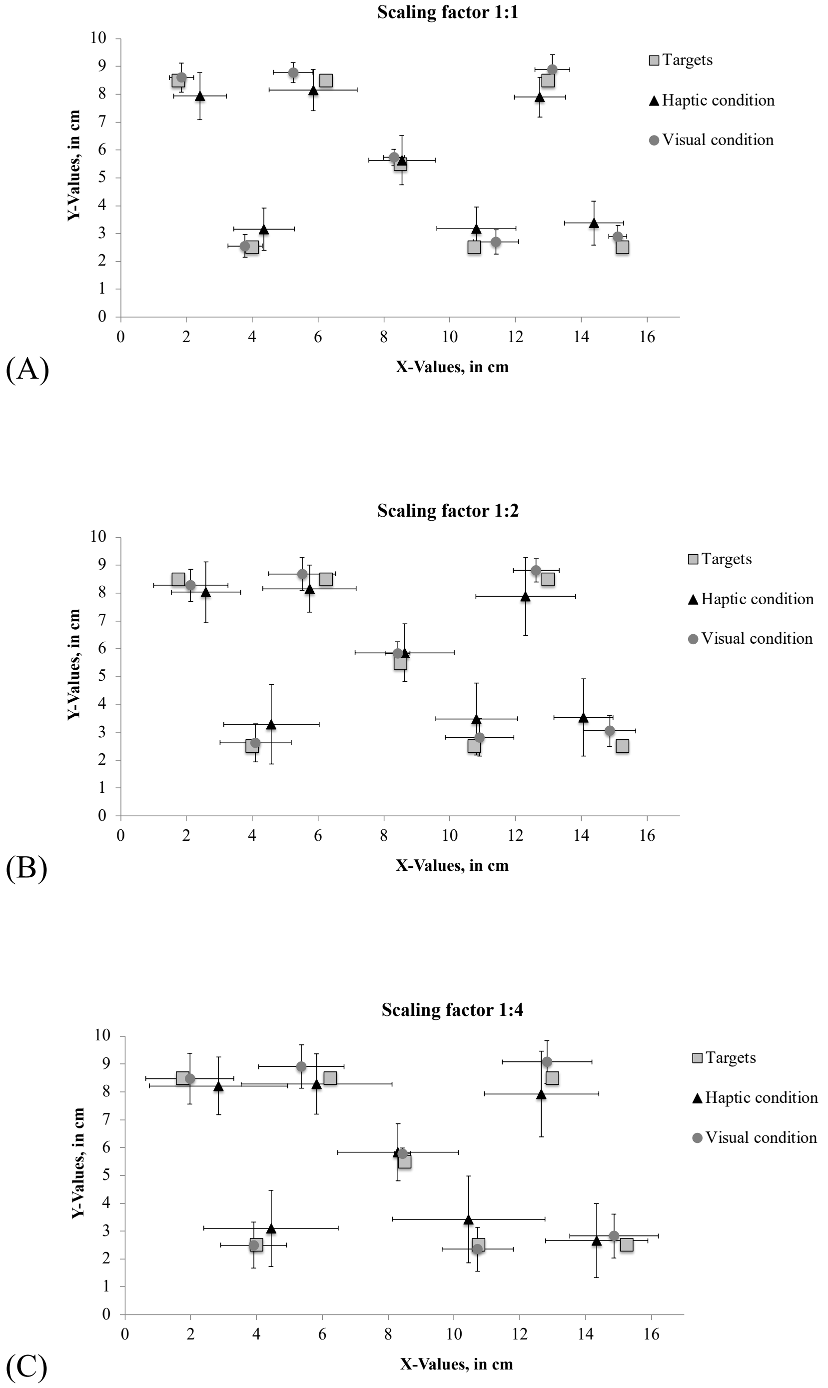

Figure 2. Scatter plots showing x- and y-coordinates of participants' responses in the scaling factors conditions 1:1 (A), 1:2 (B), 1:4 (C) and perceptual conditions (visual vs. haptic). Error bars represent standard deviation.

Table 2

Results of the ANOVAs (main effects and interactions) for absolute errors, learning times, and response times as dependent variables.

	Absolute errors			**Learning times**			**Response times**		
	F	***p***	**η_p^2**	***F***	***p***	**η_p^2**	***F***	***p***	**η_p^2**
Perceptual condition	93.32	< .001	76	73.53	< .001	.71	78.64	< .001	.72
Scaling factor	16.33	< .001	.35	24.86	< .001	.45	6.42	.005	.17
Order of perceptual condition	8.57	.006	.22	.03	.86	.00	.03	.87	.00
Perceptual condition x Order of perceptual condition	9.69	.004	.24	.98	.33	.03	.84	.37	.03
Scaling factor x Order of perceptual condition	3.88	.026	.12	1.13	.33	.03	2.37	.10	.07
Scaling factor x Perceptual condition	1.34	.27	.04	11.55	< .001	.28	1.42	.25	.04
Scaling factor (haptic condition)		-		28.43	< .001	.48		-	
Scaling factor (visual condition)		-		3.20	.08	.10		-	

Table 3

Results of the ANOVAs (main effects and interactions) for the horizontal and vertical signed errors.

	Horizontal signed errors			**Vertical signed errors**		
	F	***p***	**η_p^2**	***F***	***p***	**η_p^2**
Target location	16.02	< .001	.42	.40	.67	.02
Target location x Perceptual condition	8.24	.006	.24	5.11	.009	.16
Target location x Order of perceptual condition	4.38	< .001	.17	2.36	.10	.08
Target location (haptic condition)	10.79	< .001	.32	1.74	.18	.04
Target location (visual condition)	12.61	< .001	.35	6.97	.002	.20
Target location (“haptic first”)	13.28	< .001	.57		-	
Target location (“visual first”)	7.81	< .001	.39		-	

Signed errors.

To explore the pattern of errors that was produced on the horizontal and vertical axis, we conducted an ANOVA for horizontal signed errors as dependent variable. Target location, perceptual condition (visual vs. haptic) and scaling factor (1:1 vs. 1:2 vs. 1:4) served as within-participant variables and order of perceptual condition (haptic first vs. visual first) as a between-participants variable (see Table 3 for inferential statistics)[3]. Target location referred to the accurate target location on the x-coordinate for each particular trial and thus, is identical to the x-coordinate of targets on maps with the scaling factor of 1:1 (cf. Appendix). There was a significant main effect of target location and a significant interaction between target location and perceptual condition. Separate ANOVAs conducted for each perceptual condition showed that in the haptic condition, the pattern of errors was best explained by a linear function $F(1, 23) = 16.56$ $p < .001$, $\eta_p^2 = .42$. In the visual condition, the pattern of results was better explained by a polynomial function, $F(1, 23) = 28.97$, $p < .001$, $\eta_p^2 = .56$ (see Fig. 3). Whereas adults in the haptic condition gravitated towards the midpoint, participants in the visual condition seemed to split the space into two halves and gravitated towards the center of each half.

---

[3] In these analyses with signed errors, it is crucial to look at participants' answers for each target location and thus, collapsing data across trials, is not possible. Because of our outlier analyses, there were some data missing in the data matrix. Thus, the sample included in these analyses is limited to only 24 participants ($n = 11$ in "haptic first", $n = 13$ in "visual first").

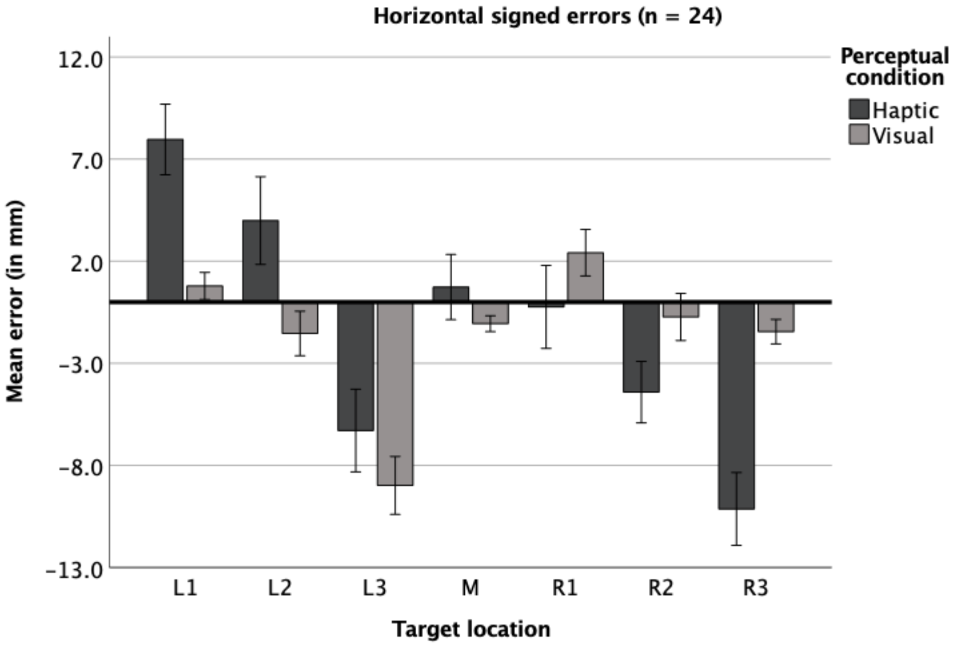

Figure 3. Mean horizontal signed errors for each target location in the perceptual conditions (haptic vs. visual). L1, L2 and L3 indicate left targets, M indicates the midpoint, and R3, R2 and R1 indicate the right targets (cf. Appendix for more information). Negative values show that answers were located too far to the left on the referent space; positive values show that answers were located too far to the right on the referent space. Error bars represent ± 1 standard error.

There was also a significant interaction between target location and order of perceptual condition. For the "haptic first" group, the results were best explained by the linear function $F(1,10) = 17.80$ $p = .002$, $\eta_p^2 = .64$ (see Fig. 4A), whereas in the "visual first" group it was again better explained by a polynomial function $F(1,12) = 18.97$ $p < .001$, $\eta_p^2 = .61$ (see Fig. 4B). Therefore, it seems that adults seemed to split the space into two halves and gravitated to each center particularly when being presented with the visual condition first.

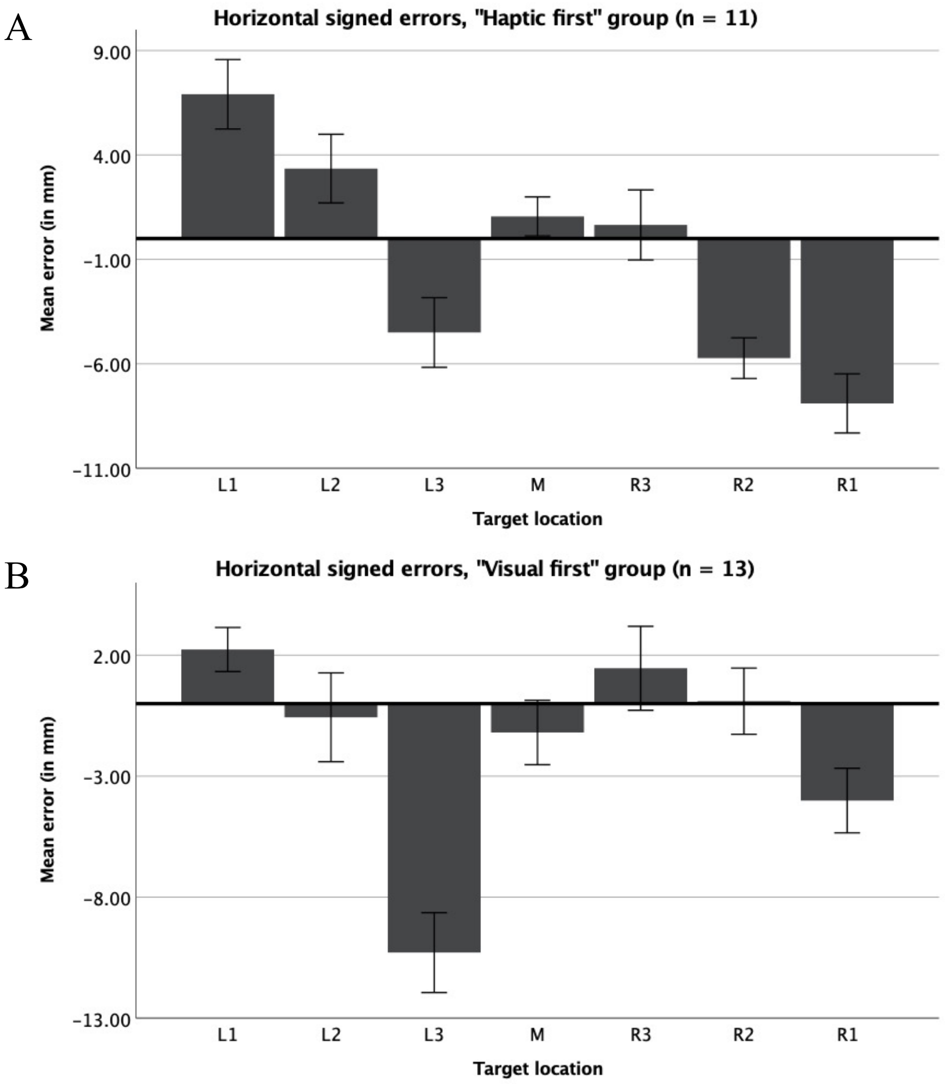

Figure 4. Mean horizontal signed errors produced for each target location, collapsed for both perceptual conditions (haptic and visual), and presented separately for the "haptic first" group (panel A) and the "visual first" group (panel B). L1, L2 and L3 indicate left targets, M indicates the midpoint, and R3, R2 and R1 indicate the right targets (cf. Appendix for more information). Negative values show that answers were located too far to the left on the referent space; positive values show that answers were located too far to the right on the referent space. Error bars represent ± 1 standard error

An analogous ANOVA was then conducted for vertical signed errors as a dependent variable, with target location (top vs. middle vs. bottom), perceptual condition (visual vs. haptic) and scaling factor (1:1 vs. 1:2 vs. 1:4) as within-participant variable and order of perceptual condition (haptic first vs. visual first) as a between-participants variable[4]. Target locations referred to the accurate location of targets on the y-coordinate, and more concrete to top (85 mm), middle (55 mm), and bottom locations (25 mm). These locations were identical to the y-coordinate of targets on maps with the scaling factor of 1:1 (cf. Appendix). The only significant effect was an interaction between target location and perceptual condition (see Table 3 for inferential statistics). The follow-up analysis revealed that the effect of target location was only significant in case of the visual condition, which was best explained by the linear function, $F(1, 28) = 10.16$ $p = .004$, $\eta_p^2 = .27$. As can be seen in Fig. 5, adults – especially in the visual condition – seemed to place the disc closer to themselves.

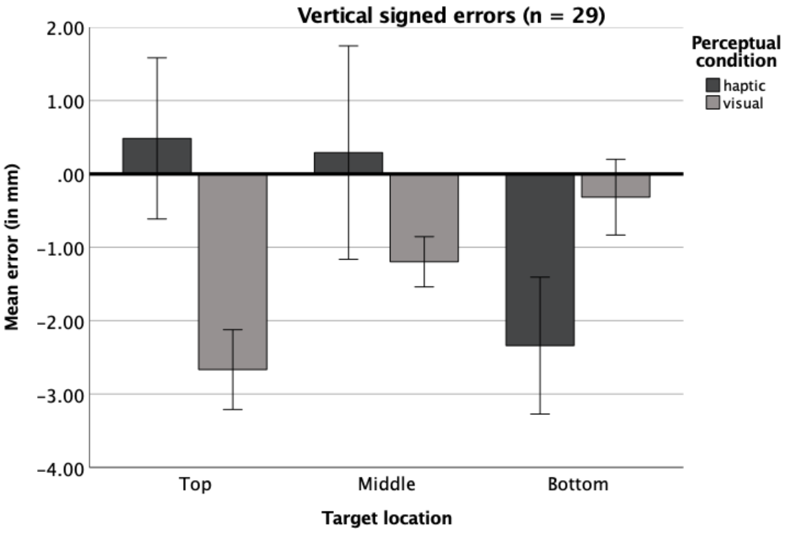

Figure 5. Mean vertical errors produced for each target location (top, middle, bottom) in each perceptual condition (haptic vs. visual). Negative values indicate that the answers were

---

[4] Similar to analysis with horizontal signed errors, the data matrix revealed some missing values after the outlier analysis and the sample is restricted to 29 participants (*n* = 14 in "haptic first", *n* = 15 in "visual first").

located too far to the bottom on the referent space; positive values indicate that the answers were located too far to the top on the referent space. Error bars represent ± 1 standard error.

Learning times.

To see wether participants' learning times differed as a function of scaling factor and perceptual condition, we computed an ANOVA with scaling factor (1:1 vs. 1:2 vs. 1:4) and perceptual condition (visual vs. haptic) as within-participant variable and order of perceptual condition (haptic first vs. visual first) as a between-participants factor (for inferential statistics, see Table 2). There was a significant main effect of perceptual condition due to longer learning times in the haptic than visual condition ($M_{\text{haptic}} = 14.53$, $SE_{\text{haptic}} = 1.26$; $M_{\text{visual}} = 4.33$, $SE_{\text{visual}} = 0.58$, $p < .001$). Additionally, the ANOVA yielded a significant effect of scaling factor, which was qualified by a significant interaction between scaling and perceptual condition. Separate ANOVAs computed for each perceptual condition revealed that the learning times decreased linearly with higher scaling factor in the haptic condition only, whereas learning times remained constant across scaling factors in the visual condition. As can be seen in Table 1, it seems that participants in the haptic condition needed more time to learn about the target locations in maps with the same size as the referent space (scaling factor 1:1) as opposed to smaller-scaled maps. Order of perceptual condition did not seem to affect participants' learning times (all *p*s > .10).

Response times.

We computed an ANOVA with participants' response times as dependent variable, scaling factor (1:1 vs. 1:2 vs. 1:4) and perceptual condition (visual vs. haptic) as a within-participant variable and the order of perceptual condition (haptic first vs. visual first) as a between-participants variable (for inferential statistics, see Table 2). The analysis yielded a significant effect of scaling factor, which was best described by a linear function, $F(1, 31) = 10.02$, $p = .004$, $\eta_p^2 = .25$. Participants showed higher response times with increasing scaling factors ($M_{1:1} = 9.02$, $SE_{1:1} = 0.63$; $M_{1:2} = 9.47$, $SE_{1:2} = 0.69$; $M_{1:4} = 9.61$, $SE_{1:4} = 0.69$). The effect of the perceptual condition was also significant, because participants responded slower in the haptic ($M = 13.20$, $SE = 0.99$) than in the visual condition ($M = 5.53$, $SE = 0.52$). There was no significant interaction between scaling factor and perceptual condition, suggesting that in both perceptual conditions, response times increased linearly with higher scaling factor. In addition, the effect of order was not significant and neither were any of its interactions (all *p*s > .10). Overall, it seems that participants produced longer response times in the haptic as opposed to the visual condition. Crucially, findings indicated that response times increased linearly with higher scaling factors which was found for the visual as well as the haptic perceptual condition.

Discussion

The current study investigated adults' spatial scaling from memory in two different perceptual conditions: a visual and a haptic (blindfolded) condition. Importantly, we tested spatial scaling abilities in each of these conditions while at the same time, addressing methodological constraints of previous research (e.g., Szubielska & Möhring, 2019; Szubielska et al., 2019, 2021). That is, we manipulated scaling factors systematically, separated exploration phases from localizing the target, and assessed participants' response times as well as localization errors.

Based on our results obtained for absolute errors and response times, it seems that participants of both perceptual conditions used mental transformation strategies in order to solve the spatial scaling task. More concrete, it was found that absolute errors and response times increased with higher scaling factors in each perceptual condition, in line with findings from mental imagery research (e.g., Kosslyn, 1973; 1975; Shepard & Metzler, 1971; Szubielska & Bałaj, 2018) and previous studies on spatial scaling in the visual and haptic domain (Möhring et al., 2014; 2016; Szubielska & Möhring, 2022). At the same time, our findings contrast studies that did not reveal evidence that blindfolded participants used mental transformation strategies (Szubielska & Möhring, 2019; Szubielska et al., 2019; 2021). The differences in methodologies may explain these contrasts. In the current research, participants had to scale distances from memory whereas in previous studies the map was available during the entire spatial scaling task (Szubielska & Möhring, 2019; Szubielska et al., 2019).

Scaling from memory may have increased the likelihood that the current study helped discovering participants' mental transformation strategies for two reasons. First, separating the exploration phase from the phase in which the scaling process takes place is a crucial precondition in order to measure response times accurately in the haptic condition. Second, performing the task from memory in the current study may have increased participants' tendency to use an allocentric reference frame which consequently increased response accuracy. Previous studies have found that introducing a delay between perceiving a target and giving a response has led to a more allocentric performance pattern (for a review, see e.g., Postma et al., 2008). Although we tried to keep this delay to a minimum in order to minimize cognitive load, the short length of this delay may have been sufficient to elicit an allocentric reference frame.

Moreover, in the current study, targets on the maps varied on two dimensions which contrasts a previous study in which targets on the maps varied on only one dimension (Szubielska et al., 2021). Previous research showed that two-dimensional conditions are more error-prone than one-dimensional conditions because of their complexity (Frick & Newcombe, 2012; Szubielska et al., 2019). Hence, it may be the case that this complexity increased the likelihood of participants using mental transformation strategies as this is a more effective strategy for memorizing complex maps and scaling them by zooming into the space (i.e., mentally transforming the mental image, see also Szubielska & Möhring, 2022).

Our results also suggest that the order of perceptual condition had an influence on participants' ability to scale from memory. Our findings showed that participants in the haptic condition produced larger absolute errors than in the visual condition—but only when being tested in the haptic domain first. Importantly, the learning times in the haptic condition did not differ due to the order of perceptual blocks. Therefore, it seems that the differences in absolute errors do not exist because participants learned the maps more or less carefully in different order conditions. These findings may indicate that participants' visualization of haptically perceived stimuli was more accurate when participants had the opportunity to see what the maps looked like, as opposed to perceiving the stimuli haptically for the first time. These findings are in line with research demonstrating that adults have a tendency to visualize spatial stimuli even when the input is not visual (Pantelides et al., 2016; Szubielska, 2014; Szubielska & Zabielska-Mendyk, 2018; Vanlierde & Wanet-Defalque, 2004). At the same time, our results question the concept of functional equivalence of spatial images from touch and vision (Giudice et al., 2011) as participants showed similar accuracy of spatial scaling only after having the opportunity to perceive maps visually (first). One reason may refer to sighted individuals' unfamiliarity with convex graphics. Future studies may train participants in reading embossed pictures before testing, and investigate whether participants still differ between the orders of perceptual conditions.

The observed differences in the pattern of horizontal signed errors between the haptic and visual modalities are similar to findings of previous research (Szubielska et al., 2021). In the haptic modality, it seems that participants tended to gravitate towards the center of the perceptual space whereas the same participants seemed to split the space in two halves in the visual domain and then gravitated towards the center of each half (cf. Plumert et al., 2019).

Our results are in line with the category adjustment model (Huttenlocher et al. 1991) and suggest that participants tended to encode the referent space as one entity in the haptic condition but used more fine-grained categories in the visual condition. Furthermore, the order of the perceptual conditions influenced adults' horizontal signed errors such that adults used fine-grained categories when they started with the visual condition. The results on vertical signed errors suggest that participants in the visual condition tended to give their responses closer to the bottom edge of the referent space which was closer to the participant. In turn, in the haptic condition, the vertical signed errors did not differ significantly with respect to the vertical target location.

Findings of the current study should be interpreted in light of strengths and limitations. We consider it a strength that for the first time, we have investigated spatial scaling from memory in the haptic and visual domain while concurrently addressing methodological constraints of previous research. However, with respect to our methodology, we consider it a limitation that waiting for the "start" signal given by the experimenter required inhibition from our participants. That is, they were asked to open their eyes in the visual condition or direct their hands to the table in the haptic condition. Here, it was quite difficult for some participants to refrain from self-initiated reactions as evident in the training session. We cannot exclude that this inhibitory load had a greater negative effect in the more demanding haptic condition than in the visual condition. Another limitation is that we used only three vertical locations, and therefore the conclusions about gravitating answers for the vertical dimension should be validated in subsequent experiments (using more vertical locations).

Suggestions for future research.

Our research can be further developed in theoretical and applied directions. Follow-up studies may take additional inter-modal conditions into account (learning the maps visually, responding haptically and vice versa). This approach would allow elucidating the functional equivalence of visual and tactile spatial representations, as well as the issue of amodality of cognitive maps (Giudice et al., 2011; Loomis et al., 2013; Ottink et al., 2021). Future studies may also study the specificity of spatial scaling in haptic and visual domains by conducting neuroimaging studies. Finally, examining spatial scaling strategies used by participants who are blind would yield crucial information that may help developing more effective training on map reading for blind people.

Conclusion.

Overall, the present study on adults' spatial scaling indicated mental transformation strategies in blindfolded and sighted participants and thus, qualified previous studies in the research field. Such mental transformation strategies refer to the usage of mental zooming and this kind of strategy is indicated by a specific response pattern (i.e., a linear increase in absolute errors and response times with higher scaling factors; Gilligan et al., 2018; Möhring et al., 2016). Such response patterns were found in mental imagery research (Kosslyn, 1975; Shepard & Metzler, 1971) and this similarity to previous research may suggest that the mechanism underlying spatial scaling is analogous to the mechanisms underlying other imagery operations such as scanning or rotation. Interestingly, the usage of mental transformation strategies was shown both in the visual and haptic domains. This finding may be treated as support for the idea of (supr)amodality of spatial information representation in humans (Bryant, 1997; Giudice et al., 2011; Huffman & Ekstrom, 2019; Levine & Schwarzbach, 2018; Loomis et al., 2013; Ottink et al., 2021; Wolbers et al., 2011).

In addition to these outcomes, the present study provides a methodological approach that allows investigating spatial scaling in various perceptual domains, which will help increasing our understanding of the underlying processes of this important spatial ability.

Open Practices Statement

The data for the experiment is available at the Figshare repository (https://doi.org/10.6084/m9.figshare.19217016.v1). None of materials for the experiments reported here is available and the experiment was not preregistered.

Acknowledgments and Funding Information

The research presented in this report is part of the project ALPHORN financed by the Polish National Science Centre (NCN, grant number 2019/01/Y/HS6/00049) and the Swiss National Science Foundation (SNSF, grant number 100014L_192206/1).

References

Boyer, T. W., & Levine, S. C. (2012). Child proportional scaling: Is 1/3 = 2/6 = 3/9 = 4/12? *Journal of Experimental Child Psychology, 111*(3), 516–533. https://doi.org/10.1016/j.jecp.2011.11.001

Bryant, D. J. (1997). Representing space in language and perception. *Mind & Language, 12*(3-4), 239–264. https://doi.org/10.1111/1468-0017.00047

Bundesen, C., & Larsen, A. (1975). Visual transformation of size. *Journal of Experimental Psychology, 1(3)*, 214–220. https://doi.org/10.1037/0096-1523.1.3.214

Craddock, M., & Lawson, R. (2009a). Size-sensitive perceptual representations underlie visual and haptic object recognition. *PLoS ONE, 4*(11), Article e8009. https://doi.org/0.1371/journal.pone.0008009

Craddock, M., & Lawson, R. (2009b). The effects of size changes on haptic object recognition. *Attention, Perception, & Psychophysics, 71*(4), 910–923. https://doi.org/10.3758/APP.71.4.910

Frick, A. (2019). Spatial transformation abilities and their relation to later mathematics performance. *Psychological Research, 83*, 1465–1484. https://doi.org/10.1007/s00426-018-1008-5

Frick, A., & Newcombe, N. (2012). Getting the big picture: development of spatial scaling abilities. *Cognitive Development, 27*(3), 270–282. https://doi.org/10.1016/j.cogdev.2012.05.004

Gilligan, K. A., Hodgkiss, A., Thomas, M. S. C., & Farran, E. K. (2018). The use of discrimination scaling tasks: A novel perspective on the development of spatial scaling in children. *Cognitive Development, 47*, 133–145. https://doi.org/10.1016/j.cogdev.2018.04.001

Gilligan, K. A., Thomas, M. S. C., & Farran, E. K. (2019). First demonstration of effective spatial training for near transfer to spatial performance and far transfer to a range of mathematics skills at 8 years. *Developmental Science, 23*(4), Article e12909. https://doi.org/10.1111/desc.12909

Giudice, N. A., Betty, M. R., & Loomis, J. M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *37*(3), 621–634. https://doi.org/10.1037/a0022331

Hodgkiss, A., Gilligan, K. A., Tolmie, A. K., Thomas, M. S. C., & Farran, E. K. (2018). Spatial cognition and science achievement: The contribution of intrinsic and extrinsic spatial skills from 7 to 11 years. *British Journal of Educational Psychology, 88*(4), 675–697. https://doi.org/10.1111/bjep.12211

Huffman, D. J., & Ekstrom, A. D. (2019). A modality-independent network underlies the retrieval of large-scale spatial environments in the human brain. *Neuron*, *104*(3), 611–622. https://doi.org/10.1016/j.neuron.2019.08.012

Hund, A. M., Plumert, J. M., & Recker, K. M. (2020). Visually scaling distance from memory: Do visible midline boundaries make a difference? *Spatial Cognition & Computation, 20*(2), 134–159. https://doi.org/10.1080/13875868.2020.1734601

Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review, 98*(3), 352–376. https://doi.org/10.1037/0033-295X.98.3.352

Huttenlocher, J., Newcombe, N., & Sandberg, E. H. (1994). The coding of spatial location in young children. *Cognitive Psychology, 27*(2), 115–148. https://doi.org/10.1006/cogp.1994.1014

Huttenlocher, J., Newcombe, N. S., & Vasilyeva, M. (1999). Spatial scaling in young children. *Psychological Science, 10*(5)*,* 393–398. https://doi.org/10.1111/1467-9280.00175

Kosslyn, S. M. (1973). Scanning visual images: Some structural implications. *Perception and Psychophysics, 14*(1), 90–94. https://doi.org/10.3758/BF03198621

Kosslyn, S. M. (1975). Information representation in visual images. *Cognitive Psychology, 7*(3), 341–370. https://doi.org/10.1016/0010-0285(75)90015-8

Larsen, A., & Bundesen, C. (1978). Size scaling in human pattern recognition. *Journal of Experimental Psychology: Human Perception & Performance, 4*(1), 1–20. https://doi.org/10.1037/0096-1523.4.1.1

Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics, 71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439

Levine, S. M., & Schwarzbach, J. V. (2018). Cross-decoding supramodal information in the human brain. *Brain Structure & Function*, *223*(9), 4087–4098. https://doi.org/10.1007/s00429-018-1740-z

Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2013). Representing 3D space in working memory: Spatial images from vision, hearing, touch, and language. In S. Lacey & R. Lawson (Eds.), Multisensory imagery (pp. 131–155). Springer Science + Business Media. https://doi.org/10.1007/978-1-4614-5879-1_8

Möhring, W., Frick, A., & Newcombe, N. S. (2018). Spatial scaling, proportional thinking, and numerical understanding in 5- to 7-year-old children. *Cognitive Development, 45*, 57–67. https://doi.org/10.1016/j.cogdev.2017.12.001

Möhring, W., Newcombe, N. S., & Frick, A. (2014). Zooming in on spatial scaling: preschool children and adults use mental transformations to scale spaces. *Developmental Psychology, 50*(5), 1614–1619. https://doi.org/10.1037/a0035905

Möhring, W., Newcombe, N. S., & Frick, A. (2015). The relation between spatial thinking and proportional reasoning in preschoolers. *Journal of Experimental Child Psychology*, *132*, 213–220. https://doi.org/10.1016/j.jecp.2015.01.005

Möhring, W., Newcombe, N. S., Levine, S. C., & Frick, A. (2016). Spatial proportional reasoning is associated with formal knowledge about fractions. *Journal of Cognition and Development, 17*(1), 67–84. https://doi.org/10.1080/15248372.2014.996289

National Research Council (2012). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas.* National Academies Press.

Ottink, L., Hoogendonk, M., Doeller, C. F., Van der Geest, T. M., & Van Wezel, R. (2021). Cognitive map formation through haptic and visual exploration of tactile city-like maps. *Scientific Reports*, *11*(1), Article 15254. https://doi.org/10.1038/s41598-021-94778-1

Pantelides, S. N., Kelly, J. W., & Avraamides, M. N. (2016). Integration of spatial information across vision and language. *Journal of Cognitive Psychology, 28*(2), 171–185. https://doi.org/10.1080/20445911.2015.1102144

Plumert, J. M., Hund, A. M., & Recker, K. M. (2019). Is scaling up harder than scaling down? How children and adults visually scale distance from memory. *Cognition, 11,* 39–48. https://doi.org/10.1016/j.cognition.2018.12.013

Postma, A., Zuidhoek, S., Noordzij, M. L., & Kappers, A. M. L. (2008). Keep an eye on your hands: On the role of visual mechanisms in processing of haptic space. *Cognitive Processing, 9*(1), 63–68. https://doi.org/10.1007/s10339-007-0201-z

Srinivas, K., Greene, A. J., & Easton, R. D. (1997). Visual and tactile memory for 2-D patterns: effects of changes in size and left‐right orientation. *Psychonomic Bulletin & Review, 4*(4), 535–540. https://doi.org/10.3758/BF03214345

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://doi.org/10.1126/science.171.3972.701

Siegel, A. W., Herman, J. F., Allen, G. L., & Kirasic, K. C. (1979). The development of cognitive maps of large- and small-scale spaces. *Child Development, 50*(2), 582–585. https://doi.org/10.2307/1129440

Szubielska, M. (2014). Strategies for constructing spatial representations used by blind and sighted subjects. *Studia Psychologica, 56*(4), 273–285.

Szubielska, M. (2015). Mental majorization of figures tactilely explored by sighted and congenitally blind individuals. *Roczniki Psychologiczne/Annals of Psychology*, *18*(1), 121–132. https://doi.org/10.18290/rpsych.2015.18.1-5en

Szubielska, M., & Bałaj, B. (2018). Mental size scaling of three-dimensional objects perceived visually or tactilely. *Advances in Cognitive Psychology*, *14*(3), 139–149. https://doi.org/10.5709/acp-0245-5

Szubielska, M. & Möhring, W. (2019). Adults' spatial scaling: Evidence from the haptic domain. *Cognitive Processing, 20*(4), 431–440. https://doi.org/10.1007/s10339-019-00920-3

Szubielska, M., & Möhring, W. (2022). Blindfolded adults use mental transformation strategies for spatial scaling of tactile maps. *Scientific Reports*, *12*(1), Article 6275. https://doi.org/10.1038/s41598-022-10401-x

Szubielska, M., Möhring, W., & Szewczyk, M. (2019). Spatial scaling in congenitally blind and sighted individuals: Similarities and differences. *Journal of Cognitive Psychology, 31*(4), 476–486. https://doi.org/10.1080/20445911.2019.1624554

Szubielska, M., Szewczyk, M., & Möhring, W. (2021). Differences in adults' spatial scaling based on visual or haptic information. *Cognitive Processing*. Advance online publication. https://doi.org/10.1007/s10339-021-01071-0

Szubielska, M., Zabielska-Mendyk. E. (2018). Memorizing 2D tactile right-angle-shapes by congenitally blind and sighted adults. *Studia Psychologica, 60*(3), 137–149. https://doi.org/10.21909/sp.2018.03.758

Uttal, D. H., Sandstrom, L. B., & Newcombe, N. S. (2006). One hidden object, two spatial codes: Young children's use of relational and vector coding. *Journal of Cognition and Development, 7*(4)*,* 503–525. https://doi.org/10.1207/s15327647jcd0704_4

Vanlierde, A., & Wanet-Defalque, M. C. (2004). Abilities and strategies of blind and sighted subjects in visuo-spatial imagery. *Acta Psychologica*, *116*(2), 205–222. https://doi.org/10.1016/j.actpsy.2004.03.001

Vasilyeva, M., & Huttenlocher, J. (2004). Early development of scaling ability. *Developmental Psychology, 40*(5), 682–690. https://doi.org/10.1037/0012-1649.40.5.682

Wolbers, T., Klatzky, R. L., Loomis, J. M., Wutte, M. G., & Giudice, N. A. (2011). Modality-independent coding of spatial layout in the human brain. *Current Biology*, *21*(11), 984–989. https://doi.org/10.1016/j.cub.2011.04.038

Appendix. Target location (in mm) on the referent space.

Target location (horizontal)	X-coordinate	Y-coordinate
L1 (first from the left)	17.5	85
L2 (second from the left)	40	25
L3 (third from the left)	62.5	85
M (the middle)	85	55
R3 (third from the right)	107.5	25
R2 (second from the right)	130	85
R1 (first from the right)	152.5	25