Vision Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

A comparison of haptic material perception in blind and sighted individuals

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ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form 21 January 2015
Available online xxxx

Keywords:
Material perception
Haptic perception in blind humans
Perceptual space

ABSTRACT

We investigated material perception in blind participants to explore the influence of visual experience on material representations and the relationship between visual and haptic material perception. In a previous study with sighted participants, we had found participants' visual and haptic judgments of material properties to be very similar (Baumgartner, Wiebel, & Gegenfurtner, 2013). In a categorization task, however, visual exploration had led to higher categorization accuracy than haptic exploration. Here, we asked congenitally blind participants to explore different materials haptically and rate several material properties in order to assess the role of the visual sense for the emergence of haptic material perception. Principal components analyses combined with a procrustes superimposition showed that the material representations of blind and blindfolded sighted participants were highly similar. We also measured haptic categorization performance, which was equal for the two groups. We conclude that haptic material representations can emerge independently of visual experience, and that there are no advantages for either group of observers in haptic categorization.

1. Introduction

In recent years, the interest in investigating the perception of object surface properties, such as material classes and material properties, has been growing. One goal has been to examine how different material surface properties or more generally textures are perceptually organized and represented in different modalities (Baumgartner, Wiebel, & Gegenfurtner, 2013; Bergmann Tiest & Kappers, 2007; Bhushan, Rao, & Lohse, 1997; Fleming, Wiebel, & Gegenfurtner, 2013; Hollins et al., 2000, 1993; Okamoto, Nagano, & Yamada, 2013; Picard et al., 2003; Rao & Lohse, 1996). In a previous study, we found the visual and haptic material representations of sighted participants to be highly congruent (Baumgartner, Wiebel, & Gegenfurtner, 2013). However, material categorization performance was better with visual material exploration than with haptic exploration. Even though the two senses are separate systems in material perception, they seem to be tightly coupled. In the present study, we want to investigate the coupling between vision and haptics further by comparing congenitally blind participants who lack any visual experience to blindfolded sighted participants.

Two questions concerning material perception in blind participants are treated here: Do the mental representations of materials differ between sighted and blind participants, and are there differences in material categorization performance between the two groups? On the one hand, one might expect an altered representation in blind participants because they lack visual guidance in haptic experience and visual imagery. On the other hand, blind observers have more extensive training on haptic stimuli. This might provide them with benefits when categorizing materials and might lead to a different perceptual organization of material properties.

So far little research has been conducted on how blind participants tactually perceive natural materials. In contrast to individuals with intact vision, blind people presumably rely more on the tactile sense to orient themselves in the world, for example to read or to navigate. The general idea of compensation between the senses has been proposed by Diderot in the 18th century (Diderot, 1770/1916). Indeed, blind Braille readers have been shown to possess enhanced spatial acuity in a grating orientation task (Goldreich & Kanics, 2003; Stevens, Foulke, & Patterson, 1996; Van Boven et al., 2000; but see Grant, Thiagarajah, & Sathian, 2000). However, other authors have found no tactile

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http://dx.doi.org/10.1016/j.visres.2015.02.006
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superiority in blind people (Grant, Thiagarajah, & Sathian, 2000; Heller, 1989a). These diverging results might be explained by acquired tactile experience (Van Boven et al., 2000; Wong, Gnanakumaran, & Goldreich, 2011). Specifically, extensive training through Braille reading may lead to an advantage in tactile acuity tasks.

Several studies have investigated the perception of shapes or pictures in the form of raised-line drawings in blind participants, especially since such tangible images and maps could be useful for blind individuals. The results here are mixed, with some studies reporting advantages for blind (D'Angiulli, Kennedy, & Heller, 1998; Heller, 1989b) and some reporting better performance of sighted participants (Bailes & Lambert, 1986; Heller et al., 2002; Lederman et al., 1990), or no difference (Picard et al., 2010). Factors such as experience with the type, size and nature of the displays, and task demands surely play a role in the inconsistency of the results. Another factor that has repeatedly been investigated and quite probably influences performance in such tasks is the time at which individuals have become blind. It has often been shown that late blind and blindfolded sighted participants outperform congenitally blind participants in tasks involving raised line drawings (e.g., Heller, 1989b; Heller et al., 1996). However, D'Angiulli, Kennedy, and Heller (1998) investigated blind and sighted children and found blind children to outperform the control group when they were allowed to explore the stimuli actively. Nevertheless, the often observed advantage of late blindness emphasizes the role of visual experience in tactile perception. According to Lederman et al. (1990), visual imagery could be crucial for object representation in the tactile domain. This has also been shown for shapes. In a study using bell peppers in a shape discrimination task, Norman and Bartholomew (2011) showed that congenitally blind participants performed worse than participants with acquired blindness, even though they showed a tendency of enhanced tactile acuity compared to both late blind and sighted participants.

But how much does visual experience and visual learning contribute to the perceptual representations of material properties and the categorization of material classes in the haptic modality? To our knowledge, the only study that has investigated some aspects of material perception in blind participants has been conducted by Heller (1989a). Heller used sandpaper in a roughness discrimination task and found no difference between congenitally blind, late blind and sighted participants. The question remains whether this pattern of results generalizes to a broader range of different tasks and material qualities. We wanted to investigate whether the perceptual interpretations of material properties in the haptic sense are represented similarly or differently in the two groups of observers. Since material categories are tightly linked to material property judgments (Fleming, Wiebel, & Gegenfurtner, 2013), we also tested whether there are performance differences in the categorization of materials.

First, we compared the semantic representation of material properties by means of a principal components analysis (PCA) in congenitally blind and sighted participants. Secondly, we compared the categorization performance of congenitally blind and sighted participants.

2. Materials and methods

2.1. Participants

Five blind participants (one female, four male) performed both tasks (see Table 1). All but one were right-handed. Four of them were congenitally blind, and one was born with severe visual deficits and turned fully blind at 6 months of age. They received financial compensation for their participation in the experiment. All participants gave informed consent prior to data collection. The work was carried out in accordance with the principles laid down in the Declaration of Helsinki.

Table 1
Blind participants.

Number	Sex	Age	Cause of blindness	Age of onset	Handedness
1	m	34	Retinal degeneration	Birth	r
2	m	19	Retinopathia praematurorum	Birth	l
3	m	24	Cancer	Birth	r
4	f	22	Glaucoma	Birth	r
5	m	32	Retinitis Pigmentosa	6 months	r

2.2. Data from sighted participants

The data for sighted participants was derived from Baumgartner, Wiebel, and Gegenfurtner (2013). Twelve sighted participants had taken part in this study, an additional five participants had provided the categorization data. Sighted participants had been blindfolded during haptic material exploration.

For the present study, the number of stimuli was reduced from 84 to 70 for the blind participants in order to reduce testing time. In addition, purely visual properties of the previous study were eliminated (i.e., glossiness, colorfulness, and texture). Otherwise, the present study was conducted as the previous one. For comparison with the blind participants, the eliminated material samples and properties were omitted in the analysis of sighted participants haptic data. We only used data from those six participants who had completed the haptic ratings before the visual ratings to exclude effects of visual experience with our stimulus set in sighted participants.

2.3. Stimuli

Our stimuli consisted of 70 material samples (14×14 cm in size) that were glued onto pieces of 12 mm thick medium density fiberboard (MDF). Stimuli comprised seven general material categories (10 stimuli/category): plastic, paper, fabric, fur and leather, stone, metal, and wood. Our stimuli can be seen in Fig. 1.

2.4. Material properties

We asked our participants to rate seven material properties accessible to the haptic sense on a 7-point Likert scale.

2.4.1. Roughness

How rough or smooth does the material appear to you? Low values indicate that the surface feels smooth; high values indicate that it feels rough.

2.4.2. Orderliness

How ordered or chaotic does the material appear to you? Low values indicate that the material's surface shows no regularities but rather is random or chaotic. High values mean that the surface has an ordered, regular structure.

2.4.3. Hardness

How hard or soft does the material appear to you? How much force would be required to change the shape of the material? Low values indicate that the surface feels soft; little force is required to change the shape of the material. High values indicate that it feels hard and cannot easily be deformed.

Please cite this article in press as: Baumgartner, E., et al. A comparison of haptic material perception in blind and sighted individuals. *Vision Research* (2015), http://dx.doi.org/10.1016/j.visres.2015.02.006

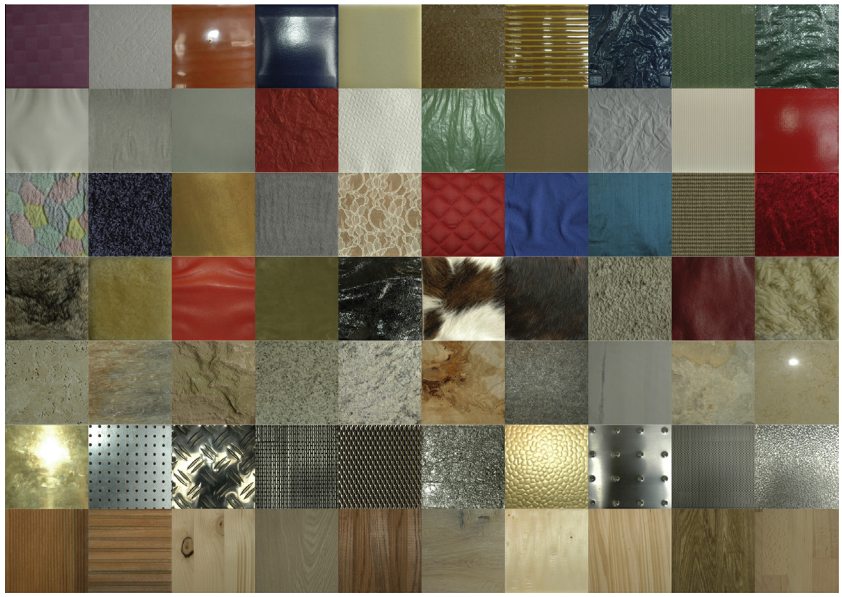

Fig. 1. Stimuli used in the experiment. From top row to bottom row: plastic, paper, fabric, leather/fur, stone, metal, wood.

2.4.4. Warmth

How warm or cold does the material appear to you? Low values indicate that the material feels warm or body temperature; high values indicate that the material feels cold to the touch.

2.4.5. Elasticity

How elastic or stiff does the material appear to you? Low values indicate that the material is not elastic. It is either stiff or its form remains changed after deformation. High values indicate the material is very elastic. After deformation, it will return to its original form.

2.4.6. Friction

How high does the friction of the material appear to you? Low values indicate that the material has low friction and is slippery. High values indicated that you feel a lot of friction when touching the material.

2.4.7. Three-dimensionality

How three-dimensional does the material's surface appear to you? Low values indicate that the surface is flat, high values indicate that the surface has a three-dimensional structure.

2.5. Procedure

Participants sat in front of a table with a pedestal for the material samples. At the beginning of each block, the participant was read a written description of the material property. The order of blocks, i.e., material properties, was randomized for each participant. The order of stimuli was also randomized for each participant but the same in each block. Participants wore earphones over which we presented auditory broadband noise during the trials. As soon as the correct material stimulus had been placed onto the pedestal by one of the experimenters, the other experimenter started the auditory noise, which signaled the beginning of the manual exploration to the participant. After 13 s, the mean frequency of the auditory broadband noise became higher, which signaled the participant to end the exploration. The noise stopped completely after another 2 s. Participants were allowed to freely explore the materials with their right hand but we asked them to neither scratch nor knock onto the materials and not to explore the edges of the material samples. At the end of each trial, the participant would verbally give his/her response to the experimenters; this was entered into a Matlab GUI.

2.6. Categorization tasks

After the property ratings, the categorization task was conducted. Participants were presented with each stimulus in a newly randomized order. They had 13 s to explore the stimulus in the same manner as in the rating task. They were read the list of stimulus categories repeatedly beforehand and were asked to remember them. In each trial they had to verbally assign the stimulus to one of the given material classes *Plastic*, *Paper*, *Fabric*, *Leather/Fur*, *Stone*, *Metal*, and *Wood*.

3. Results

3.1. Ratings

In general, participants agreed rather well in their ratings. Interparticipant correlations were higher in the sighted group ($M = 0.70$, $SD = 0.42$) than in the blind group ($M = 0.62$, $SD = 0.81$) (see Fig. 2). This difference was statistically significant ($t = 3.3$, $p = 0.003$).

The general pattern of ratings, as expressed by correlations between material property ratings, proved to be rather similar for the two groups, with highest correlations between friction and roughness (sighted: $r = 0.81$, blind: $r = 0.90$) as well as friction and three-dimensionality (sighted: $r = 0.70$, blind: $r = 0.72$), and negative correlations between temperature and hardness (sighted: $r = -0.79$, blind: $r = -0.73$) as well as temperature and elasticity (sighted: $r = -0.81$, blind: $r = -0.71$) (see Fig. 3).

There is a difference between the correlations orderliness – friction and orderliness – three-dimensionality for the two groups of participants. Correlations are smaller for sighted participants. In other words, the judgments on orderliness seem to be more dependent on friction and three-dimensionality for blind participants.

For both participant groups, we performed principal component analyses (PCAs) over the mean property ratings (z-transformed) for all material samples in order to see how the material samples were represented in the semantic material property space. PCs reveal the

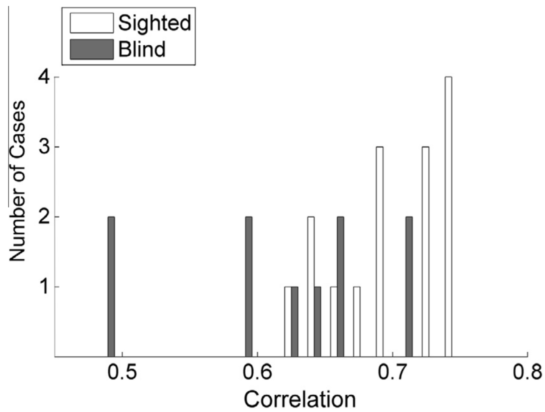

Fig. 2. Histogram of all inter-participant correlations.

underlying structure of multidimensional data. The principle components describe the directions of maximum variance in the data. The scree plots for both PCAs indicated that the data was represented best by two or three components. Here, we plot only two dimensions in the following figures for reasons of comprehensibility (Fig. 4). The first principal component explained 41.83% of the variance in the PCA based on sighted participants' data. For blind participants, 44.29% of the variance was explained by the first factor. The second principal component explained 34.09% and 34.43% of the variance for the sighted and the blind participants, respectively, and the third principal component 13.46% and 9.43%.

For sighted participants, hardness, elasticity, and (low) temperature loaded highest on the first component. It is best interpreted as a dimension of "toughness". The second component can be interpreted as "raggedness", with high loadings for both roughness and friction. The third principal component can be interpreted as "regularity" and is dominated by orderliness. For blind participants, the pattern is similar, except that the order of the first two components is changed. The first component is "raggedness", with high loadings for roughness and friction, and the second one is "toughness", described by the properties hardness, elasticity, and temperature. Again, "regularity" is the third component. The three components can be considered highly similar, the only difference between the two groups being the order of the first two components (Table 2).

In order to compare the configurations of material samples between the two PCA spaces in a formal manner, we conducted a procrustes superimposition. The procrustes superimposition uses rotation, translation and linear scaling in order to compare the two distributions within principal component space. These transformations are permitted because they leave the overall structure of the representation constant. The remaining distances between material samples in sighted and blind participants' principal component spaces are shown in Fig. 4c. These distances are rather small, which argues for a highly similar semantic representation in the two participant groups. As shown in Table 2, the third principal component was dominated by the orderliness dimension and was highly similar between both groups of participants to begin with.

With the exception of plastic, the material categories we used differ mainly along the "toughness" dimension, whereas "raggedness" and further components vary considerably within each category. Note that the remaining distances mainly extend diagonally, along the category clusters. A possible interpretation of this finding is that representations of materials are dominated by stable attributes that distinguish between different categories (i.e., "toughness", which is an intrinsic material property), while other, within-category attributes (e.g., "raggedness", which can be changed by the manufacturing process), make the perceptual representation more fine-grained and help to distinguish between individual samples.

3.2. Categorization

In addition to the rating task, we asked participants to categorize the 70 material stimuli (Fig. 5). On average, 68% of the stimuli were correctly assigned to their material class. We found substantial differences between material classes; see Fig. 6. However, sighted and blind participants performed similarly, with 66.6% accuracy for sighted participants and 68.6% for congenitally blind participants. Also, the pattern of correct and incorrect categorizations is comparable for the two groups. Lower accuracies were achieved for paper, stone, and metal, while, in terms of 'hits', both groups performed well with plastic and wood. Plastic, however, had a large number of 'false positives', but this was similar in both participant groups.

We wanted to compare the haptic material categorization behavior between our sighted and blind participants to the classification results a linear classifier would achieve based on the material property ratings. With the classifier, we wanted to see how much categorical information is contained in the property ratings, and if this differed between our two groups of participants. Such a

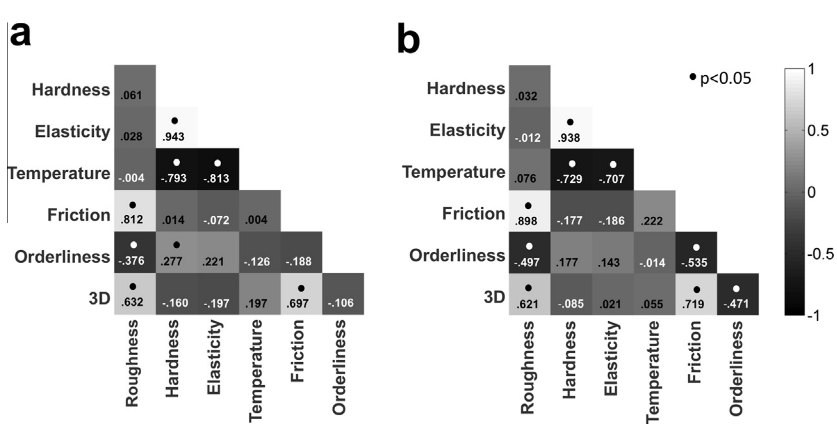

Fig. 3. Correlation matrices between material properties across the different material categories and participants. Ratings on each property dimension were averaged over all participants for each stimulus separately. The left side (a) shows sighted participants data, the right side (b) shows blind participants' data. Significant correlations are indicated by a dot. White numbers indicate negative correlation coefficients, black numbers indicate positive correlation coefficients.

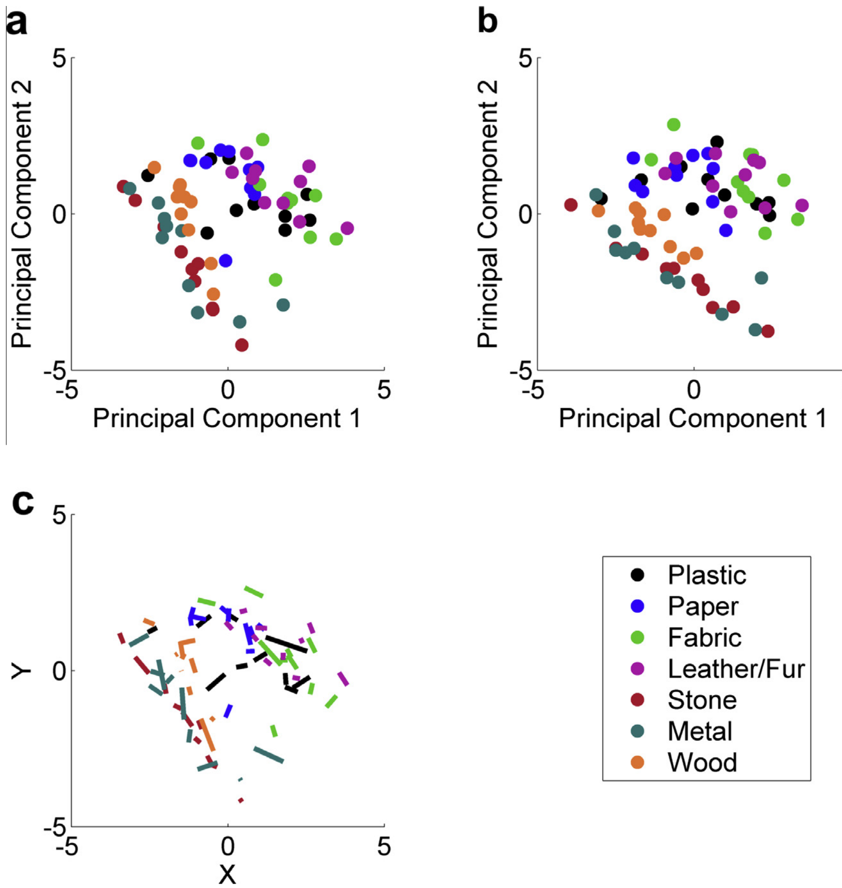

Fig. 4. Representation of the different material classes based on sighted (a) and blind (b) participants: material property ratings within a two-dimensional PC space. PCAs were performed based on the *z*-standardized property ratings for each stimulus averaged across participants. The third graph (c) depicts the procrustes superposition between the PCAs in (a) and (b). Lines indicate the remaining distances between the stimulus locations in the two spaces.

Table 2
Factor loadings for the first three principal components revealed by the two PCAs in for the sighted and blind participants. Loadings with an absolute value higher than 0.4 are printed in bold numbers.

	"Toughness"		"Raggedness"		"Regularity"	
	Sighted	Blind	Sighted	Blind	Sighted	Blind
Roughness	0.240	−0.339	**−0.542**	**−0.421**	0.112	−0.272
Hardness	**−0.490**	**−0.499**	−0.313	0.325	−0.022	−0.150
Elasticity	**−0.503**	**−0.504**	−0.285	0.312	0.062	−0.115
Temperature	**0.463**	**0.442**	0.279	−0.298	−0.163	−0.359
Friction	0.259	−0.244	**−0.523**	**−0.493**	−0.151	−0.239
Orderliness	−0.248	0.194	0.115	0.364	**−0.900**	**−0.830**
3D	0.326	−0.300	**−0.403**	−0.393	−0.353	−0.121

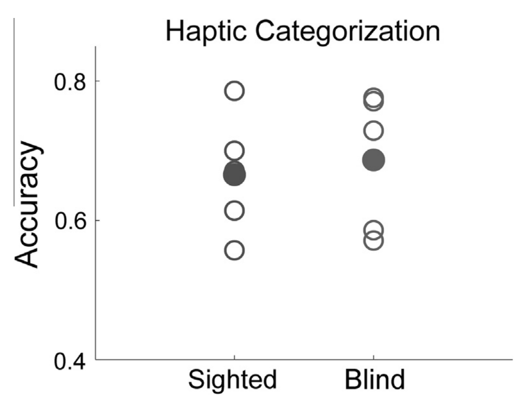

Fig. 5. Categorization accuracies for individual participants (open circles) and mean categorization accuracies (filled circles).

potential difference might also have been observed in the PCA plots but not necessarily. Therefore we conducted this analysis to look at this in a more formal and detailed fashion. We applied a linear discriminant analysis (see for example Tatsuoka & Lohnes, 1988) to the 70 material samples with a leave-one-out cross-validation. This was implemented in Matlab using the 'classify'-function (TheMathWorks Inc., 2007, Natick, MA, USA). Because our number of samples was rather limited, we used the option 'diaglinear' to reduce the number of estimates in the covariance matrix.

The classifier was run 70 times for each group. Each single observation (i.e., each stimulus) was used once as the test sample, while all other observations were used as training samples ("leave-one-out"). This procedure counteracts overfitting as test and training data remain independent. As features, the classifier was given the 7 different material property ratings (averaged across participants) for each stimulus. The classifier's accuracy was similar for both types of rating data. Using the ratings of the sighted observers, the classifier achieved 52.9% correct in the classification of the different materials into seven categories, and using the ratings of the blind participants, it achieved 47.1% (see Fig. 6b). The pattern of category-wise misclassifications does not entirely match the pattern of our participants' categorizations, for example with plastic, fabric and fur, where our participants, both sighted and blind, outperformed the classifier in terms of hits.

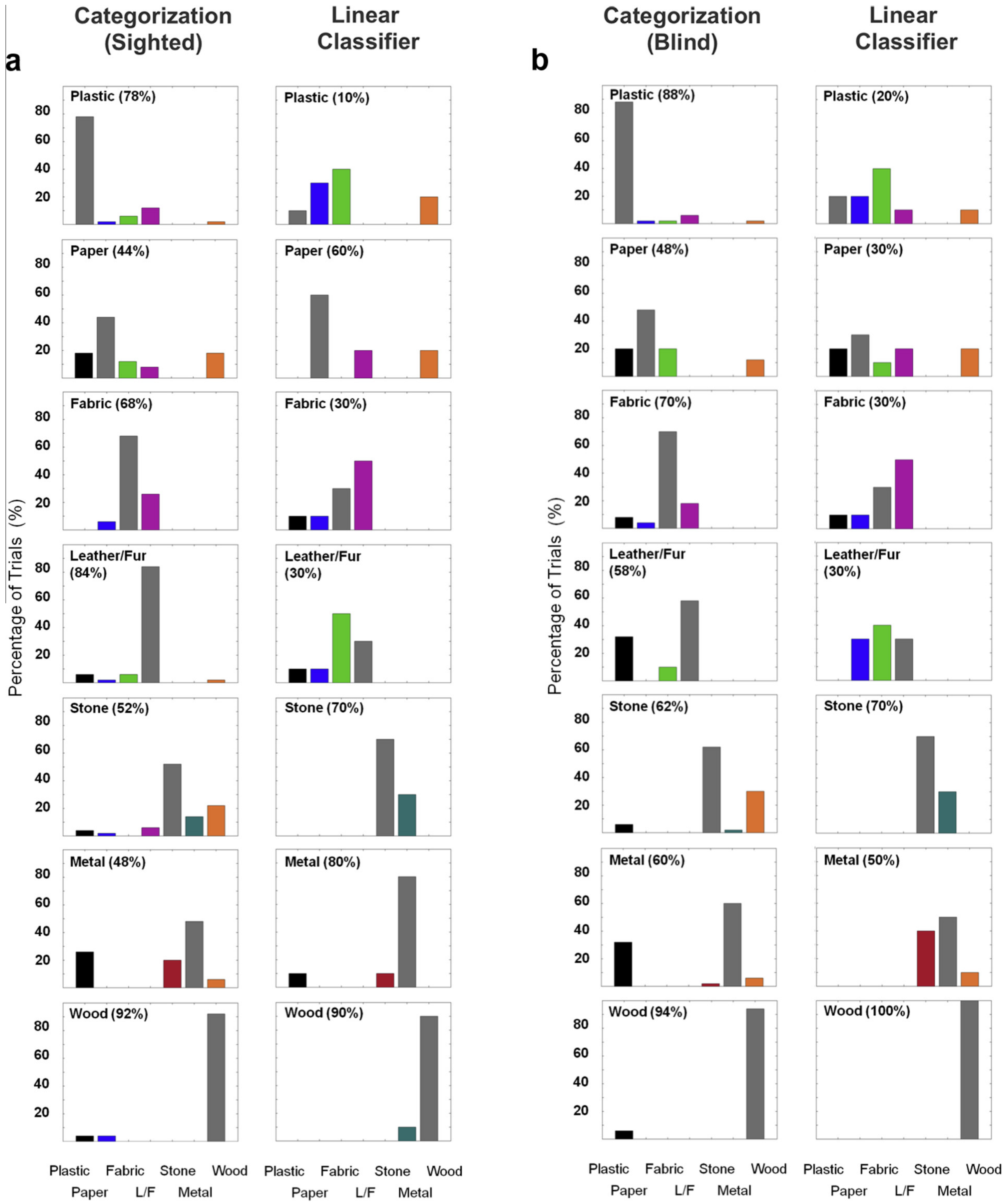

Fig. 6. Categorization and classification results for the sighted (a) and blind (b) participants: the plots in the left column show the categorization data collapsed across five observers as well as the mean categorization accuracy for each material category. The plots in the right column show the classifications of the discriminant analysis based on participants' property ratings of our stimuli.

4. Conclusions

We compared haptic material perception in blindfolded sighted and congenitally blind participants to investigate the role of visual experience in the emergence of a mental representation of materials. Most importantly, we wanted to see how similar or different haptic material representations were between these two groups of observers. Sighted and blind participants were asked to rate our stimuli according to several properties. The principal components we obtained on the ratings turned out to be highly similar for both groups of participants. The semantics of material property judgments therefore seem to be comparable for both groups. The fact that we do not find differences between the two groups of participants shows that visual experience is not necessary to shape the

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haptic perceptual representation of materials. This speaks against a crucial role of visual experience and for the fact that the haptic and visual representations of material properties are formed by similar but independent sensory experiences. In addition, we measured our participants' ability to categorize the stimuli into different material categories. Categorization performance as well as the classification results did not show significant differences between the groups.

Many studies have reported enhanced tactile acuity in blind participants (Goldreich & Kanics, 2003; Stevens, Foulke, & Patterson, 1996; Van Boven et al., 2000). This hypothesis of intersensory compensation has been studied extensively, especially in the auditory domain. Röder et al. (1999) found spatial localization of sounds in blind participants is superior to that of sighted participants. Blind participants are also more sensitive to speech (Hugdahl et al., 2004) and process speech more efficiently (Hötting & Röder, 2009; Röder et al., 2003). Blind people clearly develop superior auditory skills because they rely on sounds more than sighted people do, an argument that could hold for the haptic sense as well. This could lead both to a different sensory representation of haptic qualities and a better performance in categorization of different materials.

However, the lack of visual experience can also lead to a disadvantage in haptic perception. Congenitally blind participants performed worse in a haptic shape discrimination task than blind people who had previously made visual experiences (Norman & Bartholomew, 2011). This result emphasizes the role of visual experience in shape discrimination. This idea is strengthened by the tight link between visual and haptic object representations (e.g., Gaißert, Wallraven, & Bülthoff, 2010).

In the study presented here, we explored two aspects of material perception: how similar or differently organized is the haptic perceptual space of material properties in congenitally blind and sighted participants? And how well can the two groups of participants categorize a broad a number of material samples in their respective material classes? In essence, the question we asked here was how important visual experience is for the qualitative assessment of a collection of material properties and for the classification of material classes. In line with the idea of sensory compensation, it could be supposed that congenitally blind participants benefit from their highly trained tactile sense. This benefit could stem, for example, from more cortical processing resources for haptic information, as compared to those available for sighted people. However, a lack of visual experience could also be detrimental and lead to a different interpretation of material properties and classes.

Our results are in line with those of Heller (1989a). Congenitally blind observers did not behave differently from blindfolded sighted observers, neither in the material rating nor in the material categorization task. The absence of a performance difference could have two reasons. Either there is no benefit to visual experience guiding haptics and no benefit of enhanced haptic training, or these two factors cancel each other. In the later case both groups would have equal advantages from their background. With respect to haptic training, it is also possible that training for fine haptic discrimination does not increase the ability to correctly classify different materials. One thing is firmly shown by our results. The haptic representations are equal for blind and blindfolded sighted observers. This result does not mean that congenitally blind participants do not compensate the fact that they miss visual information by exhibiting a more trained tactile sense, but it shows that this does not lead to a different interpretation of material classes or properties.

The haptic representation seems to be guided by material categories. One of the principal components, "toughness", discriminates the categories very well. Most of the small differences between the representations of sighted and blind observers seem to fall within the categories, due to differences along the other principal component, "raggedness". Overall blind participants were somewhat less congruent in their ratings, which was reflected in slightly lower inter-participant correlations. In addition, the classifier we applied to the rating data performed a little bit worse (sighted: 52.9% and blind: 47.1%) with blind participants' ratings than with sighted participants' ratings. It is possible that these secondary findings are caused by the lack of visual experience with materials in congenitally blind people.

During our data collection, we asked the blind participants if they usually paid much attention to the materials in their surroundings or even used them as cues for navigation and other tasks. All of them negated this question. It seems that blind people do not make much use of material information in everyday life, which might be a reason for the observed lower consistency in the data.

It should be noted at this point that the similarities of the haptic representations of sighted and blind participants only holds for the properties that are accessible to the haptic sense. In our previous study, in which we compared visual and haptic property ratings of sighted people, we found that these observers can estimate some purely visual properties reasonably well through haptic exploration. They do so by making use of correlations between certain visual and haptic attributes, for example to estimate glossiness from haptic experience or temperature from visual experience. In the present study we only employed properties that can be accessed by the haptic sense, as our blind participants do not have a concept of purely visual properties. In that respect, material representations of sighted and blind participants differ. We confirmed this in informal interviews with our blind participants. In addition, it should be noted that we had only a limited number of congenitally blind participants available. Future studies using a larger pool of participants might find more fine-grained differences between blind and sighted participants in material perception tasks.

To conclude, we found the representations of haptic material properties of blind and sighted people to be remarkably similar. For the categorization task we used, we found no evidence for a better categorization performance in blind participants through sensory compensation. Nor do we find evidence for a special role of visual experience for the emergence of haptic material representations. Despite being similar, the haptic and visual representations of materials seem to arise largely independently of each other.

Acknowledgments

This work was supported by Grant DFG 879/9 to K.R.G. We thank Fiona Gericke for help with data collection.

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