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RESEARCH ARTICLE

Touch and look: The role of visual-haptic cues for categorical learning in primary school children

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Funding information

Economic and Social Research Council (ESRC) UK, Grant/Award Number: ES/K005308/1; Royal Society Wolfson Research Merit Award

Abstract

Benefits of synchronous presentation of multisensory compared to unisensory cues are well established. However, the generality of such findings to children's learning with visual and haptic sensory cue pairings is unclear. Children aged 6 to 10 years ($N = 180$) participated in a novel tabletop category-learning paradigm with visual, haptic, or visuohaptic informative cues. The results indicated that combinations of complimentary visual and haptic cues facilitated learning above unisensory visual cues only in 8-year-old children. Primarily, however, haptic information was found to dominate children's category learning across ages, particularly in the youngest children (6-year-olds), even with equal discriminability of haptic and visual exemplars. These findings suggest developmental changes in the ability to effectively combine unrelated visual and haptic information for categorical learning. Implications for the use of non-pertinent visuohaptic cues in learning tasks within educational settings at different ages, and in particular the dominance of haptic stimuli for children's learning, are discussed.

Highlights

- A novel category learning task examined the role of unisensory and multisensory visual and haptic information in children's learning.

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- Haptic cues dominated learning from 6 to 10 years of age, particularly when combined with visual information in older children.
- Findings infer protracted development of benefits in combining visuohaptic cues, and dominance of haptic over visual information for category learning.

KEYWORDS

category learning, haptic, modality dominance, multisensory, visuohaptic, development

1 | INTRODUCTION

Formal learning environments are dynamic and multisensory, with educational tools often requiring children to effectively utilize inputs to multiple sensory modalities. In particular, the inclusion of haptics (active manual exploration; Lederman & Klatzky, 2009) alongside other sensory cues to support learning is often promoted in educational contexts (Carlson & Sullivan, 1999; Ferguson & Hegarty, 1995) and has been found to augment adult learning (Kontra, Goldin-Meadow, & Beilock, 2012; Kontra, Lyons, Fischer, & Beilock, 2015). However, little empirical research has examined the benefits of incorporating haptic information into children's learning tasks or whether children are able to successfully combine haptic information with cues from other senses to support learning.

The facilitative effects of presenting multisensory stimuli compared to unisensory cues are well documented, most notably in aiding object perception or reaction times (e.g., Lewkowicz, 2000; Seitz, Kim, & Shams, 2006; Shams & Seitz, 2008). Indeed, multisensory integration (Bahrack & Lickliter, 2000) has been studied extensively in adults (Fifer, Barutchu, Shivdasani, & Crewther, 2013; Lehmann & Murray, 2005; Seitz et al., 2006; Shams & Seitz, 2008) and infants (Bahrack, Flom, & Lickliter, 2002; Bahrack & Lickliter, 2000; Bahrack, Lickliter, & Flom, 2004; Gogate & Bahrack, 1998; Lewkowicz, 2000; Lewkowicz & Kraebel, 2004; Richardson & Kirkham, 2004), with multisensory information becoming integrated progressively more effectively across childhood (Barutchu, Crewther, & Crewther, 2009; Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Bales, & Mareschal, 2015). Consequently, "multisensory" learning tools are consistently employed within children's learning environments (e.g., Baines, 2008), with multisensory interventions often recommended, particularly for children with reading and mathematical difficulties (Bryant & Bradley, 1985; Hulme, 1979; Jordan, Suanda, & Brannon, 2008; Ofman & Shaevitz, 1963; Taghvayi, Vaziri, & Kashani, 2012; Thornton, Jones, & Toohey, 1983).

A number of recent studies have reported that children's learning is facilitated to a greater extent following exposure to multisensory compared to unisensory cues, even when the two informative cues are only arbitrarily related and are not necessarily integrated into a unitary percept (Baker & Jordan, 2015; Broadbent, Osborne, Mareschal, & Kirkham, 2019; Broadbent, White, Mareschal, & Kirkham, 2017; Jordan & Baker, 2011; Kirkham, Rea, Osborne, White, & Mareschal, in press). For example, Broadbent et al. (2017) found that incidental learning of categorical information was more enhanced with combined, but irrelevant, auditory and visual cues than unisensory cues in primary school children, a facilitatory effect that improved between 6 and 10 years of age. Findings such as these are particularly pertinent given that in formal learning environments, cues to different sensory modalities may not always be related, even when both may be informative to learning.

To date, the majority of studies examining the role of complimentary multisensory cues in children's learning have focused on the efficacy of combining auditory and visual stimuli (audiovisual), with little exploration of whether the facilitation effects of multisensory cues extend to other sensory combinations, such as the simultaneous

presentation of haptic and visual cues. Indeed, within educational research, there has been much emphasis on visual and auditory feedback in interactive multisensory learning environments but little emphasis on the role of other sensory cues including haptics (Moreno & Mayer, 2007).

Both visual and haptic modalities are important and ubiquitous in children's learning, with the senses of vision and touch constantly employed during our exploration of the environment (Lederman & Klatzky, 2009). Despite this, it is not clearly understood whether the inclusion of haptic stimuli alongside the use of visual cues would reliably enhance learning over and above unisensory cues, in the same way as with audiovisual learning (e.g., Broadbent et al., 2017).

In adults, unisensory haptic cues have been reported as relatively ineffective for learning (Lederman, Klatzky, Chataway, & Summers, 1990). Others have claimed that haptic-based object recognition is inferior to visual recognition abilities (Bryant & Raz, 1975) and that the use of haptic cues can even lead to mistakes in adult's understanding of scientific concepts (Castillo, Waltzer, & Kloos, 2017). These findings have been extended to children, suggesting that across development, visual recognition of objects is almost always superior to haptic (Lederman & Klatzky, 2009), with visual information often outweighing haptic information during object exploration (Klatzky, Lederman, & Metzger, 1985). However, the dominant modality on a given task has been found to differ substantially depending on whether children are making visual or haptic estimates (Mjsceo, Hershberger, & Mancini, 1999). Moreover, Mjsceo et al. found that this haptic/visual dominance varies developmentally, with a change from visual dominance in 6-year-olds to haptic dominance in 12-year-olds.

Despite reports of haptic information being less favourable than visual cues, children as young as 2.5 years of age are able to accurately determine the identity of many occluded familiar objects using haptic-only information, with total precision by 5 years of age (Bigelow, 1981). Similar findings have been seen in 3- to 8-year-olds, with more accurate and thorough exploration patterns of haptic objects in the oldest children (Morrongiello, Humphrey, Timney, Choi, & Rocca, 1994). For instance, Bushnell and Baxt (1999) also reported that haptic recognition in 5-year-olds was remarkably accurate, albeit insufficient for transferring this information to visually identifying previously manipulated objects. Purpura, Cioni, and Tinelli (2017) extended these findings, indicating there is a progressive maturation of the ability to identify familiar objects in a cross-sensory fashion (i.e., visual-to-haptic) throughout the pre-school and primary years.

These seemingly opposing findings of the efficacy of haptic cues may be reflective of the way in which haptic information was manipulated by participants across different studies. For instance, more accurate object perception was found to arise from exploration of objects with two hands instead of just one (Lederman & Klatzky, 1987). This is particularly salient given that young children do not systematically use their hands to explore occluded objects, potentially limiting the extent of information they can acquire from haptic cues (Kalagher & Jones, 2011).

Although there are mixed results regarding the role of unisensory haptic information in object-recognition tasks in children, combinations of visuohaptic information have been found to improve perceptual accuracy by increasing the information content available (Newell, Bülthoff, & Ernst, 2003). In one early study, preschool children were reported to perform better at object recognition following a combination of haptic manipulation and visual inspection of an object than after visual inspection alone (Denner & Cashan, 1967). Conversely, Millar (1971) found that in 3- and 4-year-olds, visual recognition of nonsense shapes was not improved with the presentation of redundant haptic cues, but by 4 years of age, visual cues were effective in improving haptic recognition. In the abovementioned studies, however, the role of haptic-only cues was not assessed, making it difficult to reach conclusions regarding the effect of multisensory compared to unisensory-only cues on learning.

More recently, the integration of visual and haptic information has been shown to enhance spatial and perceptual judgments in children, although this was not found to be optimal in children younger than 8 years of age, with haptic information dominating perceptual judgements of size before this age and vision dominating judgements of orientation (Gori et al., 2008). In a study examining haptic discrimination thresholds, Gori, Sandini, Martinoli, and Burr (2010) suggest that in childhood, the dominance of one sense (e.g., touch for size judgements) may be related to cross-sensory calibration by the more precise sense for a given perceptual task.

In adults, vibrotactile stimuli in the form of a short vibration to the hand was found to shorten response time to visual stimuli (Diederich & Colonius, 2007). Moreover, the inclusion of synchronous (albeit irrelevant and uninformative) tactile cues was beneficial to auditory perception (Gillmeister & Eimer, 2007; Schürmann, Caetano, Jousmäki, & Hari, 2004), showing that, even when nonpertinent to the other cue, the addition of haptic information can enhance perception. Likewise, the addition of noninformative visual information can enhance perception and increase reaction times to a tactile stimulus on the arm, albeit only when the tactile task was difficult and required the individual to have a spatial representation of their body surface (Press, Taylor-Clarke, Kennett, & Haggard, 2004).

Despite these findings from perceptual and object recognition tasks in older children and adults, to our knowledge, there is no research examining the role of visuohaptic information on school-aged children's learning. This is particularly the case for tasks in which visual and haptic cues are only arbitrarily related, as is typically seen in multisensory learning tools within educational settings (e.g., Block, Parris, & Whiteley, 2008; Schlesinger & Gray, 2017). A handful of studies have identified beneficial effects of combining visuohaptic cues for children's reading, however. For instance, the addition of haptic exploration alongside visual directives in the training of letter knowledge is found to be particularly beneficial to low-skilled readers (Labat, Ecalle, Baldy, & Magnan, 2014), and visuohaptic exploration of letters was found to increase school-aged children's understanding of the alphabetic principle (Bara, Gentaz, & Colé, 2007). Bara et al suggest that the combination of visual and haptic letter exploration allows children to make stronger connections between the orthographic representation of letters and the corresponding phonological representation, leading to greater decoding abilities. However, despite these promising findings in relation to the teaching of letter knowledge, it remains unclear what the role of visual, haptic, and combined informative visuohaptic cues is on other elements of children's learning.

In the natural environment, behaviour is guided by information in multiple sensory modalities, with sensory information for learning rarely presented to one single sense, in isolation. Using a novel categorical learning task, one aim of the current study, therefore, was to examine the role of unisensory (visual or haptic) and multisensory (visuohaptic) cues in primary school children's learning. Stimuli consisted of different sensory cues that were not related, but that could equally be used to inform categorical boundaries. As seen in multisensory research both in incidental category learning (Broadbent et al., 2017) and explicit learning in children (Jordan & Baker, 2011; Kirkham et al., 2019) with audiovisual cues, it was hypothesized that when presented with both visual and haptic information that inform category boundaries, children would perform at a higher level than children given only unisensory (haptic-only or visual-only) informative cues. Age-related changes in the pattern of performance were also expected in line with previous findings of an improved multisensory facilitatory effect across middle childhood (Broadbent et al., 2017). A further focus of the current study was to examine the development of this across the primary school years, given changes with age in modality dominance between visual and auditory information (Nava & Pavani, 2013; Sloutsky & Napolitano, 2003). Indeed, given the mixed findings in adults and children regarding the effectiveness of haptic cues for perception and learning, differences between visual and haptic cues in the extent to which children are able to utilize them for learning was anticipated.

2 | METHOD

2.1 | Participants

Data from 180 children from three separate age groups, and naïve to the testing paradigms, were included in the study ($N = 60$ per group); "6-year-olds," mean age (years) = 6.22, range = 5.57–6.80, $N = 30$ males; "8-year-olds," $M = 8.23$, range = 7.73–8.73, $N = 36$ males; and "10-year-olds," $M = 10.21$, range = 9.66–10.68, $N = 28$ males. Participants in each age group were randomly allocated into one of three sensory learning conditions: visual-only (V), haptic-only (H), or visuohaptic (VH), resulting in 20 children per condition in each age group. Total sample size was determined by a priori power analysis for ANOVA main effect and interaction, based on pilot data with $N =$

162 participants. With a medium effect size (f) of 0.25 (Cohen, 1988), $\alpha = 0.05$, $df = 2$, and power $(1-\beta) = 0.80$, the projected sample size needed with this effect size (calculated using G*Power 3.1 software) is approximately $N = 159$ (53 participants per group) for this between/within group comparison. Thus, our sample size of $N = 180$ was considered adequate for the main objective of this study.

Children were recruited from local primary schools. Informed written consent was obtained from the parents of all children who participated, in line with the University ethics committee guidelines. All participants had normal hearing (or corrected-to-normal with hearing loop, $N = 1$ participant) and normal vision (or corrected-to-normal), and no known developmental or neurological disorder, as assessed on the parental consent form. All testing was conducted in a quiet room within the participant's school and children were rewarded for participating with a certificate and stickers. Testing sessions for each participant lasted approximately 15 min.

In order to examine whether there was a difference in the extent to which the visual and haptic exemplars could be readily discriminated as belonging to different categories, two separate discrimination tasks were included. A number of participants from only the youngest two groups ($N = 36$ 6-year-olds and $N = 22$ 8-year-olds) were randomly selected to receive one discrimination task condition (either visual or haptic discrimination). Findings from a preliminary (unpublished) study found no differences with age in ability to discriminate between exemplars. Discrimination tasks were not conducted with participants in the oldest group (10-year-olds). Discrimination tasks were included to determine whether any differences in performance on the category learning task could be due to differing levels of exemplar discriminability across conditions.

2.2 | Stimuli

Participants in all sensory conditions (V, H, or VH) played a tabletop game that required them to categorize "Alien Beanbods" as belonging to one of two locations (two plastic boxes, each displaying a different coloured spaceship: orange or grey). The Alien Beanbods consisted of 24 triangular beanbags, sized 12×12 cm, and with "googly eyes" and "hair" (see Figure 1). Each Beanbod was filled with various items depending on the *haptic* category (12 compressible/soft and 12 non-compressible/hard) and decorated with a different number of coloured dots (few: 2 or

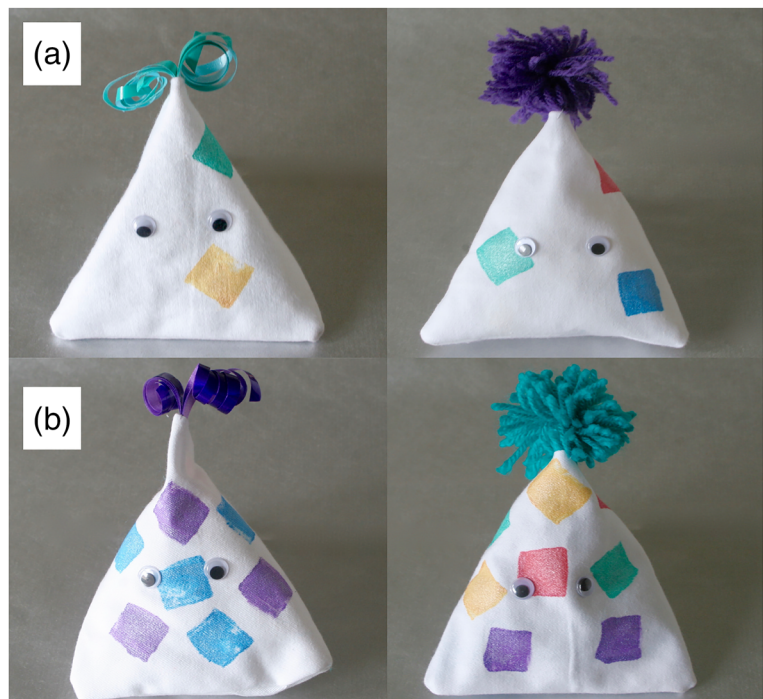


FIGURE 1 (a) Exemplars of Beanbods from Family 1 (few spots) and (b) exemplars of Beanbods from Family 2 (many spots). Hair colour (purple or green) and texture (wool or ribbon) were included as noninformative visual and haptic features across all categories

3, or many: 7 or 8) depending on the *visual* category. Informative visual cues were designed in line with research that found having “few or many” spots as visual discriminators were appropriate for use with children in this age range and resulted in greater categorical learning than with auditory-only information (Broadbent et al., 2017; Broadbent et al., 2018).

Within-category Beanbod contents also varied in weight so that this could not be used as an informative haptic cue to category membership. Non-compressible (hard) items included 20-mm polystyrene balls (*light*), pasta shells (*mid*), and ceramic baking beans (*heavy*). Whereas, compressible (soft) items included cotton-wool balls (*light*), thick sponge pieces (*mid*), and gel packs (*heavy*; see Appendix A for a full list of fillings used). Thick white cotton fabric was used so that the contents of the Beanbods could not be determined visually through the material.

Two sets of Beanbods were made for counterbalancing. In counterbalancing sensory Condition 1, the Beanbods with compressible contents were decorated with “few” spots (2 or 3) using fabric paints varying in five different colours. The other half of the Beanbods (with non-compressible items) were decorated with “many” spots (7 or 8), using the same variety of five colours across the Beanbods, for within-category variability. Counterbalancing sensory Condition 2 consisted of compressible items in the “many-spots” beanbags and non-compressible items in the “few-spots” beanbags.

Noninformative haptic and visual features on the Beanbods included two different textures of hair (curling ribbon or wool) in two different colours (purple or teal). In order for these features not to be used as indicators to category membership, but to serve as a red-herring, half of the Beanbods in each sensory condition (e.g., six compressible Beanbods with many spots) were decorated with ribbon hair (three purple, three teal) and the other half with woollen hair (three purple, three teal).

Two blue plastic fold-away boxes, sized 23 × 15 × 13 cm (L × D × H) were used as the Alien Beanbod homes; each decorated with a laminated cartoon spaceship, sized 11 × 8 cm (W × H). On one box, the spaceship was orange in colour, and on the other box, the spaceship was grey. Assignment of spaceship (to the left or right hand side of the participant) was counterbalanced across the two counterbalancing conditions mentioned above. For a schematic of the experimental set-up, see Figure 2.

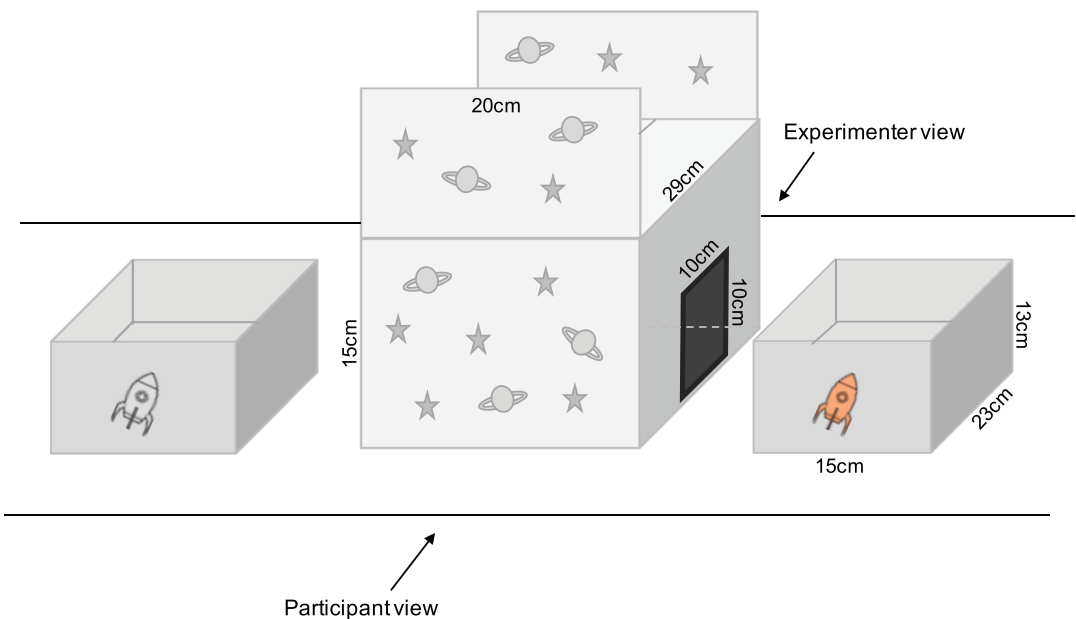


FIGURE 2 Schematic of the experimental set-up with occluder box (centre) and two “spaceship” boxes (grey and orange) as homes for the two separate categories

In the haptic-only condition, feedback from visual cues that may have informed category membership was avoided by using an occluder (“space”) box to hide the Beanbods during stimuli presentation. The dark blue occluder box, sized 29 × 20 × 15 cm (L × D × H), was adorned with silver and gold stars and planet stickers. At the end of the box facing the experimenter was a hole for the Beanbods to be inserted surreptitiously. On each side of the box, two square sections (10 × 10 cm) were cut out for participants to put their hands through and manipulate the stimuli. The two hand-holes were covered using curtains made from cream polka-dot material. To further hide the stimuli when being inserted or removed from the box, the top flaps at either end of the box were kept in the upright position.

2.3 | Design and procedure

2.3.1 | Auditory working memory

As a proxy measure for level of cognitive ability, the digit span backwards (DSB) task from the British Abilities Scale-II (BAS-II; Elliott, Smith, & McCulloch, 1996) was administered to all participants at the beginning of the testing session. This was used to establish whether each group were performing in line with expected level for age, in line with other comparable studies (e.g., Broadbent et al., 2017; Broadbent et al., 2018), and to ensure that any group-level differences in category learning performance could not be attributed to deviations from expectations of cognitive ability in each group.

2.3.2 | Category learning task

Children were seated at a table opposite the experimenter with the two spaceship boxes in front of them: one to their left and one to their right. Children were told that the game involved figuring out where each Alien Beanbod lived. The Beanbods were presented to the participants one at a time in a pseudo-random order, predetermined at the beginning of the study so that all participants received the same categorical order. Depending on sensory condition, Beanbods were either laid on the table in between the spaceships (V and VH) or put inside the occluder box, between the spaceships (H). All participants completed the 24 trials, with each of the 24 Beanbods.

In the visual-only (V) condition, children were instructed to look at the Beanbod (without touching it). In the haptic-only condition (H), children were told to put both of their hands into the “space” (occluder) box, to feel the Beanbod and then tell the experimenter in which spaceship it belonged. In the visual-haptic (VH) condition, children were instructed to look at *and* touch the Alien Beanbod in front of them (with both hands) and then tell the experimenter in which spaceship it belonged. In all conditions, the child either pointed or said which spaceship they thought the Beanbod lived in. The experimenter noted the answer and depending on whether the answer was correct or incorrect, the experimenter said: “Yes, well done it does live in the Grey (/Orange) spaceship” or “That time the Beanbod lived in the Orange (/Grey) spaceship not the Grey (/Orange) spaceship.” At the same time as giving verbal feedback regarding whether the participant was correct, the experimenter took the Beanbod and held it over the correct spaceship's box (V and VH conditions only), instead of placing the Beanbod inside. This was so that the Beanbod could then be removed and hidden away in a separate bag under the table. In the Haptic condition, the experimenter held their hand over the correct box during the verbal feedback so that no visual cues were inadvertently given. Used Beanbods were therefore hidden in all sensory conditions following exposure so that the participants in the visual conditions were not receiving further (visual) feedback throughout the task by being able to look into the spaceship boxes. Participants in the haptic condition were never given visual feedback of the Beanbods, and so all sensory conditions were kept consistent to account for this. When all 24 trials were completed, the experimenter recorded the child's reasoning about the Alien Beanbod categories (explicit categorization test) by asking “How did you decide where each Beanbod lived?” and/or “Do you know why some Beanbods lived in the grey spaceship and some lived in the orange?”

In addition to mean number correct on category learning task and explicit categorization knowledge, the number of participants who reached learning criterion (six consecutive trials correct) and mean number of trials to reach learning criterion (in participants who reached criterion) was calculated for each group across sensory conditions.

2.3.3 | Discrimination tasks

To examine whether informative cues between exemplars in the two conditions (visual and haptic) were equally discriminable, two discrimination tasks were used: one visual and one haptic, each consisting of 16 pairs of Beanbods. These tasks were used to ensure that any differences in category learning in the two unisensory conditions were not due to unequal saliency of cues between exemplars in the different categories (i.e., haptic differences [compressible vs non-compressible] were not more easily discriminable than visual differences [few vs many spots]).

The selection of 16 pairs was chosen as a subset of the full stimuli range. This was due to time constraints of testing using the full 24-pair set. The 16 sets of pairs consisted of six "identical" pairs and 10 "different" pairs. For the different pairs, five were considered minimally different (consisting of the same noninformative feature such as hair or weight) and five maximally different (differing by both informative and noninformative features).

In the haptic discrimination task, two Beanbods were presented consecutively inside the occluder box for 4 s each. Following exposure to both stimuli, the participant was asked whether they thought the two Beanbods had *felt* the same or different. Pairings of Beanbods were organized in terms of whether each one was to be compressible/non-compressible and light/heavy, and the order was predetermined at commencement of the study. In the visual discrimination condition, 32 photographs of individual Beanbods were used (16 pairs). Photographs were used for consistency across participants in order to avoid long waiting periods for participants during the sorting of visual pairings following the main task. Stimuli across the visual and haptic discrimination tasks were therefore comparable, but not identical. Photograph sets were placed face down, one pair at a time. The two photographs in the pair were then revealed individually for 4 s each one after the other, before being turned face down again. Participants were then asked whether the two beanbods had *looked* the same or different.

3 | RESULTS

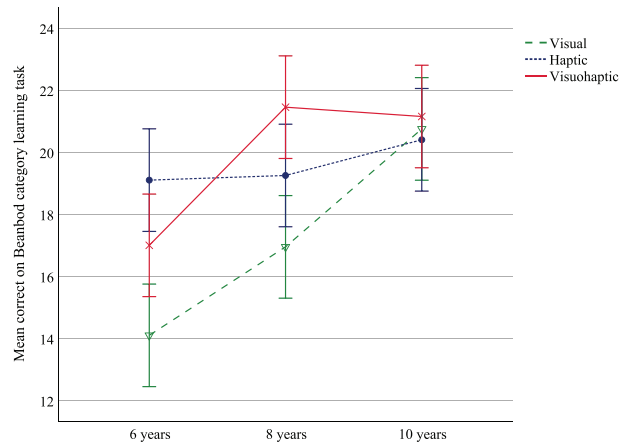
3.1 | Auditory working memory

Digit span backwards (DSB) raw ability scores were converted to standardized T-scores and compared across groups using a one-way analysis of variance (ANOVA). A significant difference was found between groups; 6 years: mean (*SD*) = 59.58 (7.06), 95% CI [57.76, 61.41]; 8 years = 52.47 (8.62), 95% CI [50.24, 54.69]; 10 years = 55.98 (9.11), 95% CI [53.63, 58.34], $F(2, 179) = 11.00$, $p < .001$, with participants in the youngest group performing at a cognitive level significantly higher than the 8-year-olds ($p < .001$) and with a trend toward a higher level than the 10-year-olds ($p = .056$). To confirm that the 6-year-olds were performing significantly below the older age groups in raw ability score, these data were also analysed. Results showed a significant effect of age; 6 years: $M = 8.83$, 95% CI [8.19, 9.48]; 8 years: $M = 11.78$, 95% CI [10.82, 12.75]; 10 years: $M = 15.25$, 95% CI [14.20, 16.30], $F(2, 179) = 50.63$, $p < .001$, with significant differences between all groups (all $p < .001$).

3.2 | Category learning task

To examine learning of category boundaries, the mean number of correct responses on the category learning task was calculated for each age group and compared across sensory learning conditions (see Figure 3). A univariate ANOVA with two between-subjects factors of age (three levels: 6, 8, and 10 years) and condition (three levels: V, H, and VH) revealed a significant main effect of age, $F(2, 171) = 17.72$, $p < .001$, $\eta_p^2 = 0.17$. This was driven by 6-year-

FIGURE 3 Mean correct on Beanbod categorization task in each modality condition across groups



olds ($M = 16.73$, $SD = 4.72$) performing significantly below 8- ($M = 19.22$, $SD = 4.32$) and 10-year-olds ($M = 20.77$, $SD = 2.73$; $p = .001$ and $p < .001$, respectively; Bonferroni-corrected post hoc comparisons), with no significant difference between 8- and 10-year-olds ($p = .074$). There was also a significant main effect of condition, $F(2, 171) = 8.71$, $p < .001$, $\eta_p^2 = 0.09$, with significantly poorer performance in the visual-cue condition than haptic ($p = .003$) and visuohaptic ($p = .001$) conditions. No significant difference was found between visuohaptic and haptic conditions ($p > .05$).

A significant age by condition interaction, $F(4, 171) = 3.86$, $p = .005$, $\eta_p^2 = 0.08$, was also found. To examine this interaction further, one-way ANOVAs were conducted for each age group separately and revealed a significant effect of condition only in 6-year-olds, $F(2, 59) = 6.76$, $p = .002$, and 8-year-olds, $F(2, 59) = 6.42$, $p = .003$, but not in 10-year-olds ($F < 1$). Six-year-olds in the visual condition performed significantly below those in the haptic condition ($p = .002$), whereas 8-year-olds in the visual condition performed significantly below those in the visuohaptic condition ($p = .002$).

3.3 | Trials to criterion (six consecutive correct)

To examine differences across groups and sensory conditions in whether participants had learned to categorize exemplars, a two-tailed chi-squared analysis of the number of participants who reached criterion of six consecutive correct was used. Results found a significant difference across sensory conditions in 6-year-olds ($\chi^2(2) = 10.42$, $p = .005$), driven by significantly fewer 6-year-olds reaching criterion in the visual condition ($N = 7$) than in the haptic condition ($N = 17$) $\chi^2(1) = 10.42$, $p = .003$. A significant difference was also found across sensory conditions in 8-year-olds ($\chi^2(2) = 10.91$, $p = .004$), driven by significantly fewer 8-year-olds reaching criterion in the visual condition ($N = 12$) than in the visuohaptic condition ($N = 20$), $\chi^2(1) = 10.00$, $p = .002$. No difference across sensory conditions was found in 10-year-olds ($\chi^2(2) = 3.75$, $p = .153$).

In participants who reached criterion, a univariate ANOVA examined the number of trials to reach learning criterion (six consecutive correct) across groups. This found no significant effects of age ($F < 1$), and only a trend toward an effect of condition, $F(2, 131) = 2.87$, $p = .060$. Fewer trials to criterion were found in the haptic (mean = 10.28, 95% CI [8.85, 11.70]) and visuohaptic conditions ($M = 10.08$, 95% CI [8.59, 11.58]) than the visual condition ($M = 12.67$, 95% CI [10.89, 14.45]). Bonferroni-corrected pairwise comparisons did not reach significance ($p > .05$).

3.4 | Explicit categorization scores

At the end of the category learning task, explicit knowledge of informative cues was examined. Participants were asked to describe verbally how they knew which Beanbod belonged to each spaceship (see Section 2 for question

encouraging a description of category boundaries). Answers were coded to determine the particular sensory cue reported as having been perceived by each participant as informative to category membership. Total numbers of correct and incorrect sensory-related comments in each condition and across age groups are presented in Figure 4).

For coding, answers were sorted into seven categories, labelled as either “none/guessed where they lived,” “visual-incorrect” (e.g., “hair colour was different”), “visual-correct” (e.g., “orange had lots of spots, grey had less spots”), “haptic-incorrect” (e.g., “grey were light and orange were fatter”), “haptic-correct” (e.g., “orange were soft, grey had hard things in”), “visuohaptic: haptic-correct, visual-incorrect” (e.g., “some were hard, some were soft. Also, maybe to do with the things on their heads?”), “visuohaptic: visual-correct, haptic-incorrect” (e.g., orange had lots of polka dots and were heavier”), or “visuohaptic-all correct” (e.g., “harder and less squares were grey, orange ones were softer and had more squares”). Answers were labelled by two individual coders (one blind to sensory condition), with an interrater reliability of 87.2%. Discrepancies were resolved together with a third coder.

Two-tailed chi-squared analyses of number of participants reporting each cue type found that in the haptic condition, all age groups reported correct haptic information with comparable frequency, $\chi^2(8) = 14.23, p = .076$. In the visual condition, 6-year-olds predominantly reported incorrect visual information above correct or other cues, $\chi^2(3) = 17.60, p = .001$, whereas older children reported correct visual information significantly more frequently, 8 years: $\chi^2(2) = 6.40, p = .041$, 10 years: $\chi^2(2) = 24.10, p < .001$.

Across age groups, children in both the haptic and visuohaptic conditions reported relying on haptic information for categorization significantly more than visual cues (6 years, haptic: $\chi^2(2) = 10.53, p = .005$, visuohaptic: $\chi^2(6) = 17.80, p = .007$; 8 years, haptic: $\chi^2(3) = 26.80, p < .001$, visuohaptic: $\chi^2(3) = 19.20, p < .001$; 10 years, haptic: $\chi^2(1) = 16.20, p < .001$, visuohaptic: $\chi^2(5) = 11.20, p = .048$).

3.5 | Discrimination tasks

Mean number correct on the two (visual and haptic) discrimination tasks conducted in 6-year-olds (visual: $M = 14.52, SD = 1.03$; haptic: $M = 14.13, SD = 1.19$) and 8-year-olds (visual: $M = 13.67, SD = 1.41$; haptic: $M = 14.77, SD = 1.09$) was analysed using a two-way ANOVA with two between-subjects variables of age (6 and 8 years) and discrimination condition (V and H). Analyses revealed no significant effect of age ($F < 1$) or discrimination condition, $F(1, 54) = 1.27, p = .265$.

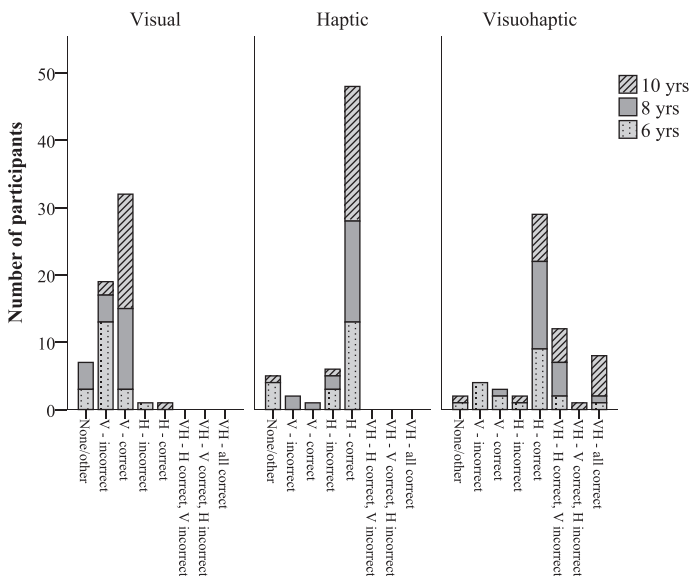


FIGURE 4 Frequency of participants across modality conditions providing each reason for categorization, in all age groups. V, visual; H, haptic; VH, visuohaptic

4 | DISCUSSION

The role of unisensory and multisensory visual and haptic information for category learning in primary school children was examined in the current study. Findings indicate haptic cues were more informative than visual cues for category learning in primary school children. In the youngest children (6-year-olds), not only did haptic information dominate performance on a category learning task at this age, but multisensory stimuli were not combined to benefit learning reliably above that seen with unisensory information. In this age group, in the VH condition, multisensory cues may have been used interchangeably across trials and across individuals, resulting in poorer performance than would be expected with cross-modal facilitation (e.g., Barutchu et al., 2009). However, this can only be speculated as driving performance in the current study. Additional work to examine within-participant performance across different learning conditions would elucidate this further.

In 8-year-old children, multisensory cues (in this case, the synchronous presentation of visual and haptic cues) were more informative than unisensory visual cues, a finding not evident in the youngest children (6-year-olds). These findings in the two youngest groups were also reflected in the number of participants who reached the criterion threshold of six consecutive correct in the different sensory conditions, suggesting further that unisensory visual cues were more difficult to learn from than haptic (for 6-year-olds) or visuohaptic (for 8-year-olds). In contrast, the oldest children (10-year-olds) performed well across all sensory conditions, indicative of the high level of performance across conditions in this group on the task. Given that multisensory stimuli did not facilitate learning to a greater extent than with unisensory haptic information in any group, these results do not fully corroborate previous findings of beneficial effects of complimentary multisensory cues for learning in children (e.g., Broadbent et al., 2017). However, given the subtle changes with age demonstrated in the current study (haptic-only to visuohaptic preference between 6 and 8 years), these findings may still remain indicative of a protracted development of multisensory integration on learning tasks (e.g., Barutchu et al., 2009; Nardini et al., 2015).

An examination across groups of the type of sensory information perceived by participants to be useful for categorizing (explicit categorization task) revealed that in the visuohaptic condition, in which both cues were available, the majority of children only mentioned the presence of haptic cues. In addition, with the majority of participants, there was either no mention of visual information or participants answered with incorrect visual cue descriptions. These findings provide insight into the effect of particular types of haptic information on learning when presented alongside other sensory information (in this case, visual). In particular, categorical haptic cues separable by a dimension of relative volume change (compressibility) were found to dominate visual cue (pattern) information in the multisensory condition, a finding reflected across age groups. Importantly, this was even found to be the case despite participants being encouraged to state all categorical information that they had perceived to be available to them. Even in the oldest group (10-year-olds), participants reported haptic information as the most salient, and predominantly as the only available cue. This was seen even with a high level of performance when presented with both visual and haptic cues simultaneously (VH) in this group.

It should be reiterated, however, that this multisensory facilitation in the 8-year-olds was not significantly greater than performance with unisensory haptic information. Nevertheless, these findings are in line with a growing body of literature suggesting that there are developmental changes in the ability to effectively use multisensory information compared to unisensory cues (e.g., Gori et al., 2008). In the study by Gori et al, which required 5- to 10-year-olds to make size judgements of objects using both visual and haptic cues, the children relied preferentially on haptic information, even when the visual information was more accurate and more reliable. Only between 8 and 10 years did children start to integrate visual and haptic information in a way that optimally benefited these perceptual judgements of size. Others have also found that multisensory information is integrated increasingly more effectively across development, providing progressively more complete and coherent representations of stimuli (Barutchu et al., 2009; Nardini et al., 2015; Nardini, Jones, Bedford, & Braddick, 2008). It is of note, however, that the current study did not examine sensory integration in the same way as the abovementioned studies. The current results using tasks in which children are able to *combine* but not *integrate* informative cues from two senses are therefore only

marginally comparable to those examining low-level perceptual integration, and may be important factor in the different findings across studies.

Studies of object perception in children that typically involve size and weight judgments have found that visual information overrides haptic input (Klatzky et al., 1985; Lederman & Klatzky, 2009), a finding not reflected in the current study. Other reports of a developmental change from visual to haptic dominance between 6- and 12-years of age (Mjsceo et al., 1999) are not corroborated by the current findings, which instead indicate haptic dominance across this age range. In the current study, however, haptic dominance was found in reference to categorical learning, as opposed to making judgements of discordantly-sized visual and haptic objects in the study by Mjsceo et al. Differences in the nature of haptic manipulation required in previous studies and the current study may also go some way to explaining these opposing findings, particularly given that the extent to which children are able to manipulate an object with both hands influences the delimiting information that can be obtained from a cue (Kalagher & Jones, 2011). For instance, the current study highlights that there may be a dominance in haptic cues when the information required for learning is categorizable by the dimension of "relative volume change" (compressibility) compared to discriminating between dimensions such as shape and texture as in previous studies. That is, haptic evaluation of geometric features of an object may be reliably less effective than with visual exploration in children, but this may not be the case for other features of haptic and visual stimuli. Furthermore, the method of haptic manipulation used in the current study, in which participants were able to use both hands to thoroughly examine exemplars and without time constraints, may also be an important distinction that contributed to seemingly opposing results across studies (see Lederman & Klatzky, 1987). Notably, the examination techniques employed by children in the current study may also be more in line with the nature of haptic exploration of learning tools within educational settings than in previous studies. A more in-depth examination of whether children's exploration patterns differed across conditions and the effect of this on learning would be an interesting avenue for future research.

The benefits of integrating multiple sources of sensory information for perception and learning are well established (Bahrick & Lickliter, 2000; Ernst & Bühlhoff, 2004; Lewkowicz, 1996; Shams & Seitz, 2008). The current findings, in line with other research into children's learning (e.g., Baker & Jordan, 2015; Broadbent et al., 2017), suggests that multisensory cues that are complimentary, but are not necessarily *integrated* into a unitary percept, can also result in enhanced learning compared to unisensory visual stimuli in children above 8 years of age. The beneficial effects of combined visual and haptic cues for object recognition (Denner & Cashan, 1967) and reading (Bara et al., 2007) in children have been reported previously. Even when synchronously presented tactile cues were unrelated to an auditory cue, it was found to facilitate perception (Gillmeister & Eimer, 2007; Schürmann et al., 2004). The current study examined this from the perspective of categorical learning, an essential aspect of children's conceptual development (Mareschal, Quinn, & Lea, 2013). That said, it is of note that in the current study, no significant differences between haptic-only and visuohaptic conditions were found, instead suggesting that the haptic cues presented in the study were dominating performance across groups. Of note here, even though raw scores for auditory working memory in the youngest children (6 years) were significantly below older children in the current study, this youngest group scored significantly above 8-year-olds on standardized scores, suggesting that this young group had a relatively high level of cognitive ability. Future studies should consider whether comparable results in relation to haptic dominance would also be seen in younger children of lower ability level.

Visual cues that differ by the dimension of "quantity of spots" (categorically, few or many) are known to be effective and easily discriminable cues (Broadbent et al., 2017; Broadbent et al., 2018), and so were incorporated into the stimuli design in the current study to alleviate potential saliency differences in visual and haptic cues. Despite this, differences in the level of saliency and discriminability of visual compared to haptic exemplars may still have driven the outcome of haptic dominance in category learning. However, no differences were found in level of discriminability between haptic and visual exemplars, and with no difference found across age groups. This indicates that the results of the category learning task were unlikely to be due to haptic category boundaries (compressibility) being more easily discriminated between than visual category boundaries (number of spots). Therefore, together with the findings from previous research, the current findings provide additional support to the particular saliency of

haptic cues for explicit category learning in school-aged children. A direct comparison of relative dominance across visual, haptic, and auditory senses would be beneficial to establish this further. Findings from across these different studies speaks to the way in which different sensory modalities dominate learning in primary school children and warrants further investigation into the role of these different senses in different learning contexts.

Our findings also highlight that the combination of cues from different senses, regardless of dominance, is progressively more effective across this age range. However, an important avenue for future investigation is whether findings of multisensory facilitation are due to having a greater number of informative cues, regardless of the sensory modality. Future research should examine comparable stimuli with two informative cues within one sensory modality (e.g., two informative visual cues). Two intra-sensory cues can bolster sequence learning reliably more than single informative cues (Kirkham, 2010). However, working memory constraints on domain-specific stores may result in multiple cues within the same sense compete for attention (Fougnie, Zughni, Godwin, & Marois, 2015). Moreover, at the perceptual level, intra-sensory cues are not as easily averaged (Trommershauser, Kording, & Landy, 2011).

The results of the current study have specific implications for the role of haptic information in educational tools. For the most part, research in the field of multisensory learning has concentrated on audiovisual integration. This is unsurprising given that auditory and visual sensory signals are readily defined and signal reliability is easily manipulated. The present study provides novel insight into the role of combining haptic cues with informative cues in another sense, in this case visual. The use of haptics (like visual cues) is ubiquitous in children's learning and an important source of information from early on in development (Bushnell & Boudreau, 1991). Furthermore, haptic information is often recognized by educators as an important sensory modality in which to present information to learners (e.g., Carlson & Sullivan, 1999; Ferguson & Hegarty, 1995). Although the dimension of relative volume change or "compressibility" may not be typically proposed in education as a useful informative cue, the results speak of the efficacy of including tactile elements to categorical learning tools for primary school children, particularly when presented alongside visual information in older children.

In summary, the results reflect a subtle change across the primary school years in the ability to use unrelated multisensory visual-haptic cues to facilitate learning above unisensory visual cues. However, the main findings indicate that, even when haptic and visual exemplars are equally discriminable, haptic information is still found to dominate perception across this age range for use in categorical learning. This was even seen in the oldest children (10-year-olds) who performed "at ceiling" on all conditions, with explicit verbal responses typically only including haptic information. When cues presented to children are separable by sensory modality, these findings suggest, therefore, that children predominantly attend to only one in order to learn category boundaries. This was even seen to be the case as multisensory information was more facilitative of learning than unisensory visual cues (e.g., in 8-year-olds). Developmental changes in the ability to effectively use a combination of unrelated visual and haptic information to benefit learning to a greater extent than with unisensory cues were also reported. These findings, therefore, have important implications for the use of combined visuo-haptic cues in learning tasks within formal education settings, as well as infer dominance of haptic over visual stimuli for category learning across childhood.

ACKNOWLEDGEMENTS

This research was supported by funding from the Economic and Social Research Council (ESRC) UK, grant reference: ES/K005308/1. D. M. was also partially funded by a Royal Society Wolfson Research Merit Award. Thanks to Hayley White who contributed to the collection of pilot data. Thanks to all the children who participated in the study and to Marshgate, Colville, St. Stephens, Sir John Lillie, Colvestone, Richard Reynolds, Morningside Primary schools, Trafalgar Infant and Junior schools, and children at the Bright Sparks project for taking part.

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How to cite this article: Broadbent H, Osborne T, Kirkham N, Mareschal D. Touch and look: The role of visual-haptic cues for categorical learning in primary school children. *Inf Child Dev.* 2019;e2168. <https://doi.org/10.1002/icd.2168>

APPENDIX A.

TABLE A1 Contents of Beanbods for counterbalancing

Content	Exemplar category	Weight	Visual features—informative	Visual features—noninformative
Cotton wool balls	Compressible	Light	2 spots, green/purple	Purple ribbon
Wrapping bows	Compressible	Light	2 spots, green/yellow	Teal ribbon
Gel packs	Compressible	Heavy	2 spots, red/blue	Purple wool
Flour	Compressible	Heavy	2 spots, red/purple	Teal wool
Quilt stuffing	Compressible	Light	2 spots, red/yellow	Purple ribbon
Flannel strips	Compressible	Medium	2 spots, purple/blue	Teal ribbon
White Tinsel	Compressible	Light	3 spots, purple, green, blue	Purple wool
Foam wedges	Compressible	Light	3 spots, red, yellow, purple	Teal wool
Sponge	Compressible	Medium	3 spots, blue, purple, yellow	Purple ribbon
Wool pom-poms	Compressible	Light	3 spots, green/yellow/blue	Teal ribbon
Playdough	Compressible	Heavy	3 spots, green/red/blue	Purple wool
Beanbag balls	Compressible	Medium	3 spots, green/red/yellow	Teal wool
Ceramic beans	Non-compressible	Heavy	7 spots, 2 blue, 2 green, 2 purple, red	Purple ribbon
Wooden beads	Non-compressible	Light	7 spots, 2 red, 2 purple, 1 green yellow blue	Teal ribbon
Decorative stones	Non-compressible	Heavy	7 spots, 2 yellow, 2 green, 2 blue	Purple wool
Mini wooden pegs	Non-compressible	Light	7 spots, 2 red, 2 purple	Teal wool
Popcorn kernels	Non-compressible	Heavy	7 spots, 2 red, 2 blue, 2 yellow, purple	Purple wool
Lego	Non-compressible	Light	7 spots, 2 red/green/purple, 1 blue	Teal ribbon
Mixed raw beans	Non-compressible	Heavy	8 spots, 4 blue, 3 purple, 1 red	Purple ribbon
Raw macaroni	Non-compressible	Medium	8 spots, 3 green, 3 blue, red, purple	Teal wool
Polystyrene balls	Non-compressible	Light	8 spots, 4 yellow	Purple ribbon
Raw penne pasta	Non-compressible	Medium	8 spots, 3 red, 3 yellow, blue, purple	Teal ribbon
Raw peas	Non-compressible	Heavy	8 spots, 2 red, 2 blue, 2 purple, green, yellow	Purple wool
Glass beads	Non-compressible	Heavy	8 spots, 2 red, yellow, green, purple	Teal wool

Note. For counterbalancing condition 1, Family 1 consisted of compressible items (haptic) and few spots (visual) and Family 2 of non-compressible items (haptic) and many spots (visual). For counterbalancing condition 2, visual features (both informative and non-informative) from Family 1 were switched with those from Family 2