

Uneven integration for perception and action cues in children's working memory

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We examined the development of visual cue integration in a desktop working-memory task using boxes with different visual action cues (opening actions) and perceptual surface cues (colours, monochromatic textures, or images of faces). Children had to recall which box held a hidden toy, based on (a) the action cue, (b) the surface cue, or (c) a conjunction of the two. Results from three experiments show a set of asymmetries in children's integration of action and surface cues. The 18–24-month-olds disregarded colour in conjunction judgements with action; 30–36-month-olds used colour but disregarded texture. Images of faces were not disregarded at either age. We suggest that 18–24-month-olds' disregard of colour, seen previously in reorientation tasks (Hermer & Spelke, 1994), may represent a general phenomenon, likened to uneven integration between the dorsal and ventral streams in early development.

Keywords: Dorsal stream; Ventral stream; Development; Search; Colour; Texture.

Introduction

Models of cortical visual processing propose a broad distinction between two extrastriate pathways (Milner & Goodale, 1995; Ungerleider & Mishkin, 1982). The dorsal stream and parietal lobe, involved in the visual control of action, take as their input mainly spatio-temporal stimulus

properties such as size, orientation, and motion (Jeannerod, 1997). High levels of the dorsal stream represent location and other properties relevant for action in body-centred coordinate frames (Andersen, Essick, & Siegel, 1985; Snyder, Batista, & Andersen, 1997). The ventral stream and temporal lobe, involved in recognition,

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process mainly surface properties, such as colour and pattern (Kobatake & Tanaka, 1994; McKeefrey & Zeki, 1997), and high levels of the ventral stream represent complex objects such as faces (Kanwisher, McDermott, & Chun, 1997). It is acknowledged, however, that the separation between dorsal and ventral stream processing is not complete, either anatomically or behaviourally (Goodale & Westwood, 2004; Jeannerod, 1999; Rossetti & Pisella, 2002). Indeed, since most everyday actions are guided partly by recognition of objects' surface features, there must be extensive interaction between "ventral" and "dorsal" representations. Selecting the most ripe apple, as judged by colour, is an example of a motor act based on a surface property processed mainly in the ventral stream.

There are many routes by which ventral information may be made available for dorsal action planning. Rossetti and Pisella (2002) present an analysis of processing between V1 and M1 based on primate studies, which indicates that the dorsal and ventral streams interact at many levels before reaching motor output. The frontal networks that project to motor areas receive both dorsal and ventral information, and, strikingly, there is no known purely dorsal pathway to the motor areas. This analysis suggests that the dorsal and ventral prefrontal and premotor cortices have a crucial role in combining dorsal and ventral visual information for action.

In early childhood, there is evidence for uneven development of dorsal and ventral stream visual processing; see below. In the present study we explicitly tested children's ability to remember combinations of "dorsal" and "ventral" visual cues. Participants had to discriminate among a novel set of objects, which were defined by the conjunction of two cues: a surface-based, action-irrelevant ("ventral stream") cue, such as colour, and a visual action ("dorsal stream") cue, such as the manual action that can be performed with the object. We measured each participant's performance on (a) the surface-based discrimination, (b) the action discrimination, and (c) discrimination for a conjunction of the two. We could therefore ask how well the abilities to use each

cue separately translated into ability to integrate the two.

Development of the dorsal and ventral visual streams

Humans orient to visual stimuli from birth using subcortical mechanisms, but over the course of development visual function comes increasingly under cortical control. Two fundamental inputs to the dorsal and ventral streams are provided by the processing of global motion and form, in areas V5/MT and V4, respectively (Braddick & Qian, 2000; Gallant, Braun, & van Essen, 1993). Functional imaging confirms that in adults, processing global motion and form activate largely nonoverlapping areas in posterior cortex (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000). In infants, there is evidence for global motion processing, seen in a preference for coherently moving dots over noise, at 3–4 months (Wattam-Bell, 1994). Global form processing is apparent at 4–5 months, shown by a looking preference and evoked potential responses for coherently oriented line segments with a concentric organization (Braddick, Curran, Atkinson, Wattam-Bell, & Gunn, 2002; Braddick et al., 2006). In later childhood, discrimination for coherent motion reaches adult levels earlier than that for coherent form (Atkinson & Braddick, 2005; Gunn et al., 2002). In perceptual colour-from-motion tasks, there is evidence that colour and motion information are increasingly dissociated over the course of development (Dobkins, 2006); this process of developmental specialization may underlie improving abilities to discriminate within a stream, at the cost of integrating information between streams.

Evoked potential studies have assessed infants' processing of faces, associated with high levels of the ventral stream, and presaccadic potentials, related to cortical control of saccades at a high level of the dorsal stream. Event-related potential (ERP) measures at 6 months show some specialization for face processing, although face responses are less specific than those from adults (de Haan, Pascalis, & Johnson, 2002). At the same age,

there is not yet evidence for adult-like signals related to parietal saccade planning (Csibra, Tucker, & Johnson, 1998). Taken together, these studies do not indicate that either “dorsal” or “ventral” processing as a whole has a faster maturational rate, but that different functions within the dorsal and ventral streams mature unevenly with respect to each other. This unevenness may give rise to unusual patterns of processing for and interaction between different visual features; see below.

The maintenance of dorsal- and ventral-stream information in memory

Momentary visual input does not always directly guide action, but is also mediated by representations held in memory. Representations in semantic memory distinguish which objects to approach or avoid, based on perceptual criteria (such as the colours that distinguish ripe from unripe apples). Working memory maintains perceptual and semantic information about nearby objects while they are out of the field of view. In adult humans and primates, maintenance of different sensory cues in working memory depends on segregated feature-selective networks that include prefrontal cortex (PFC) and parietal cortex as well as areas of sensory cortex (Pasternak & Greenlee, 2005). Within PFC, there is functional segregation with respect to sensory modalities and stimulus attributes (Levy & Goldman-Rakic, 2000), as well as integration by multimodal neurons (Fuster, Bodner, & Kroger, 2000) and those coding multiple attributes within a modality (Rao, Rainer, & Miller, 1997). In adult working memory, there is evidence for independent maintenance of dorsal- and ventral-stream visual information. Maintenance of spatial and colour information shows differential activation on functional magnetic resonance imaging (fMRI), activating, respectively, more dorsal and more ventral regions of lateral prefrontal cortex (Mohr, Goebel, & Linden, 2006; Munk et al., 2002). There are also regions in PFC whose activation is linked to maintenance of both spatial and feature information in humans (Mohr et al., 2006) and PFC neurons that code conjunctions

of the spatial and feature information in primates (Rao et al., 1997). There is behavioural evidence that spatial and colour representations in working memory depend on different resources: In adults, a conjunction judgement for both a stimulus’s colour and its orientation is as good as either of the single judgements (Mohr & Linden, 2005). Colour masks interfere with recall for stimulus colour but not location, while spatial masks interfere with location but not colour (Vuontela, Rama, Raninen, Aronen, & Carlson, 1999).

Developmental studies suggest that in young children, “dorsal” and “ventral” visual features are not held equally robustly in working memory. Generally there is an advantage for “dorsal” cues. Fixation times for objects reappearing after occlusion indicate that 10-month-olds maintain spatio-temporal but not feature information (Xu & Carey, 1996). When object features are systematically varied, individuation of objects by shape and size (relevant for both recognition and action) emerges earlier than by more purely “ventral” cues provided by texture and colour. (Wilcox, 1999). In a preferential-looking variant of a change detection task, infants’ ability to bind colour and location after a brief delay emerged between 6.5 and 7.5 months (Oakes, Ross-Sheehy, & Luck, 2006). Which cues are maintained may also vary with the nature of the stimulus. With images of faces and monochromatic asterisks, infants responded to colour or feature changes but not to location changes, whereas with images of manipulable toys they responded to location changes but not to identity changes (Mareschal & Johnson, 2003). This suggests that very young infants selectively maintain either “dorsal” or “ventral” visual information in memory.

The measures in all these infant tasks came from looking time. Action responses, for which systematic errors of visual cognition can persist to a later age than that seen on looking-time measures (e.g., Hood, Cole-Davies, & Dias, 2003), may show poor integration of “dorsal” and “ventral” visual cues into later childhood. Children aged 18–30 months show scale errors,

attempting impossible actions on miniature objects (DeLoache, Uttal, & Rosengren, 2004), consistent with incorrect integration of perceptual information for action. Another striking failure to recruit a "ventral" cue, colour, for action, is seen in disoriented children aged 18–24 months and older, who in some circumstances fail to reorient themselves using the colours of walls in small enclosures (Hermer & Spelke, 1994, 1996; but see Learmonth, Nadel, & Newcombe, 2002; Nardini, Atkinson, & Burgess, 2008). Young children's disregard of wall colour for reorientation has been interpreted in terms of the operation of a specific module for spatial reorientation (Hermer & Spelke, 1994, 1996). Here we raise the possibility that disregard of colour may be a more general developmental phenomenon linked to difficulties with recruiting visual surface cues associated with the ventral stream (e.g., colour) for action. In the present studies we asked whether children aged 18–24 and 30–36 months would show failures to integrate colour and other surface cues with visual action cues. Children were tested on a working-memory task for either visual surface or visual action properties of an object, or both.

EXPERIMENT 1

Children aged 18–24 months saw a toy hidden in one of four boxes, each of which had a unique combination of a surface-based cue (red or blue colour) and action cue (manual action needed to retrieve the toy; pull a hook or push through a curtain). After a short delay they were given a choice of boxes to search for the toy. Different conditions tested recall for box colour only, box action only, and the conjunction of the two. We predicted that the individual rates of colour and action recall would not predict the ability to use the two cues in conjunction: specifically, that as in reorientation tasks (Hermer & Spelke, 1994, 1996) colour information would be lost when it had to be combined with another cue.

Any visual difference signalling differential action possibilities ("affordances") necessarily also

appears different in a purely perceptual judgement. Our "dorsal" action cue may therefore activate both dorsal-stream representations guiding a retrieval action and ventral-stream representations that perceptually recognize a distinctive feature such as the hook. Likewise, although our "ventral" colour cue is likely to be irrelevant for dorsal-stream action planning, there is evidence for some processing of colour in the dorsal stream (Gegenfurtner et al., 1994). Therefore we note that our cues (or indeed any cues) are unlikely to elicit purely ventral or dorsal stream representations. However we term them "ventral" and "dorsal" cues based on the hypothesis that they will be differentially processed by the two streams: colour relatively more by the ventral stream, action relatively more by the dorsal.

Method

Participants

Participants were 11 children, 18–24 months old (6 male, mean age 20.8 months, *SD* 1.5 months). One further child was excluded from analysis owing to a response bias; see *Analysis*. For this and subsequent studies children were recruited from a volunteer database, and parents gave informed consent for their child's participation.

Apparatus

Four cardboard boxes, each measuring 15.5 × 15.5 × 15.5 cm, were used for hiding objects and testing recall. Each box had a different combination of colour and retrieval action; see Figure 1a. The fronts of two boxes were red (Munsell 7R 5/18), while two were blue (7PB 3/10). The bottom half of each box had a panel 11 cm wide in the centre. In two boxes this panel was removed, and an opaque white fabric hung behind it. In the other two boxes the panel was a white door with a white hook mounted in its centre; pulling the hook opened the panel upwards, giving access to the inside of the box. Searching for a toy therefore involved pushing a hand through the fabric in one case, and pulling the door up using a hook in the other. The front edges of the boxes and the left and right edges of

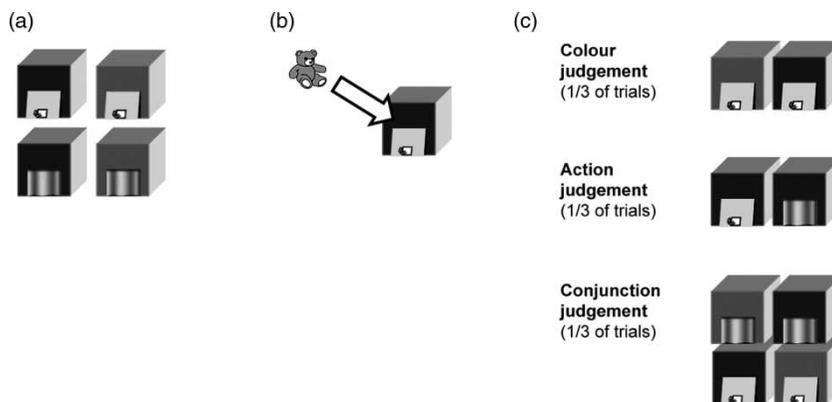


Figure 1. (a) The apparatus: four boxes, each a unique combination of colour (red or blue) and retrieval action (hook or curtain). Shades of grey are used to illustrate red and blue (the colours used did not have such a large brightness difference). (b) On each trial, participants saw a toy hidden in a box—in this example, the blue box with a hook. (c) The box was taken away and brought back alongside others, and the child was prompted to find the toy. Different conditions tested discrimination for colour, for action, and for the conjunction of the two.

the panels were outlined in black. A cardboard frame was used to present choices of either two or four boxes for search. This frame could accommodate either all four boxes in a 2×2 arrangement, or a pair of boxes side by side. A variety of small toys were used for hiding and retrieval.

Design and procedure

The child sat in a parent's lap at one side of a table, while the experimenter stood opposite. In an initial familiarization trial, all four boxes were presented in a random 2×2 arrangement, and children watched as a different toy was hidden in each. They were then encouraged to retrieve all the toys, in any order. This familiarization phase ensured that children had experience opening all the different boxes before the experiment began. If necessary, children were shown how to open the boxes at this stage. The height of the parent and child's chair was set so the child faced the centre of the 2×2 array, making it similarly easy to see and reach for all four boxes.

On each subsequent trial a single target box was shown, and the child watched as the experimenter hid a toy in this box. The experimenter narrated the hiding event, telling the child, for example, that the toy crocodile was going to hide. The target box, assigned pseudorandomly by alternation from participant to participant, remained the

same throughout the study. Using the same target throughout mirrors the procedure of Hermer and Spelke (1994, 1996), in whose reorientation task children always had to remember the same room corner, defined by a conjunction of colour and room geometry. Here, as there, the rationale for keeping the target constant (which according to some conventions makes this a reference memory task), was to exclude proactive memory interference as a source of error. We include an analysis of whether or not children incrementally learned the features of the box as the study progressed, which bears on interpretation of the task in terms of reference memory or working memory.

Once the toy was inside the box and out of view, the experimenter held the box up to draw the child's attention to it, before taking it out of view of the child and there slotting it in the frame, as part of an array of boxes to be presented in the search phase. The frame with the test boxes, including the target, was then presented to the child, who was encouraged to find the toy. On "colour" trials the correct box was presented alongside a different-colour, same-action counterpart. On "action" trials the correct box was presented alongside a different-action, same-colour counterpart. On "conjunction" trials, boxes with all four combinations of colours and actions were presented. On these trials finding the object

depends on correctly judging both colour and action in conjunction. These conditions are illustrated in Figure 1. The first box whose front panel was touched was recorded, as once a curtain or hook was touched, tactile as well as visual information was available. The array of boxes was prepared before each trial began, so that the delay before retrieval was not any longer for four-box (conjunction) than two-box (single) trials.

The experiment was structured in four blocks of six trials, each block including two of each condition (colour, action, conjunction) in a random sequence. Half of all colour trials had the target box on the left. Likewise, half of all action trials had the target box on the left. In conjunction trials the target box appeared equally often in each of the four possible positions in a 2×2 array (top left, top right, bottom left, bottom right), while the ordering of the three other boxes was generated randomly. Owing to the great difficulty in maintaining attention at this young age, many children would not complete all four blocks, but all completed at least three. Therefore in this and subsequent experiments, all those who completed at least three blocks were retained for analysis.

Analysis

On colour-only and action-only trials, children were required to discriminate between two boxes: the target and one other (see Figure 1). Each child's number of correct colour and action trials was converted to a percentage. The rate of correct search expected by chance was 50%. On conjunction trials children had a choice of four boxes. Two of these boxes were correct with respect to colour, while two were incorrect; likewise, with respect to action, two were correct and two incorrect. Therefore as in single judgements, the rates of correct use for either the colour or the action cue individually expected by chance were 50%. (The rate expected by chance for selection of the correct box, which depends on use of both cues, was 25%.)

Rates of colour-correct search were compared on paired two-tailed t tests to test the prediction that colour use would be reduced in conjunction judgements compared to single-cue judgements. Single and conjunction rates of action-correct

search were likewise compared. Single judgements for colour and action were also compared to evaluate whether baseline abilities for the two judgements were matched. To evaluate whether there was incremental learning for the cues distinguishing the correct box, which remained the same for the duration of the study, analyses of variance (ANOVAs) analysed performance by block.

There were two criteria for exclusion: a strong side bias—more than 90% responses to one side—or a strong preference for the incorrect action or colour (0 out of 6, or 0–1 out of 8 correct single action or colour judgements; a participant searching at random would score this low less than 5% of the time).

Results

Figure 2a plots mean percentage correct searches by action and colour on single judgement (two-box) and conjunction judgement (four-box) trials. Judgements for action alone were 76% correct, colour alone 61%. Both these rates were significantly above chance (50%) on one-tailed one-sample t tests; for action $t(10) = 5.72$, $p < .001$; for colour $t(10) = 2.39$, $p < .02$. Use of the action cue was also significantly more accurate than use of the colour cue on a paired t test (two-tailed); $t(10) = 2.42$, $p < .04$. Note that in conjunction judgements, correct use of either cue does not necessarily mean finding the box containing the toy. For example, of two colour-correct boxes, one is also action-correct (and contains the toy); the other is colour-correct but action-incorrect.

In the conjunction condition, when children were required to judge both action and colour, correct use of the action cue remained high at 79% and did not differ from the single action rate; $t(10) = 0.67$, $p > .5$. By contrast, correct use of the colour cue fell to chance, 47%, a rate significantly lower than for use of the colour cue on its own; $t(10) = 2.45$, $p < .04$. Therefore as predicted, when colour and action had to be judged in conjunction, use of colour fell. By contrast, in these same conjunction judgements the use of action did not change.

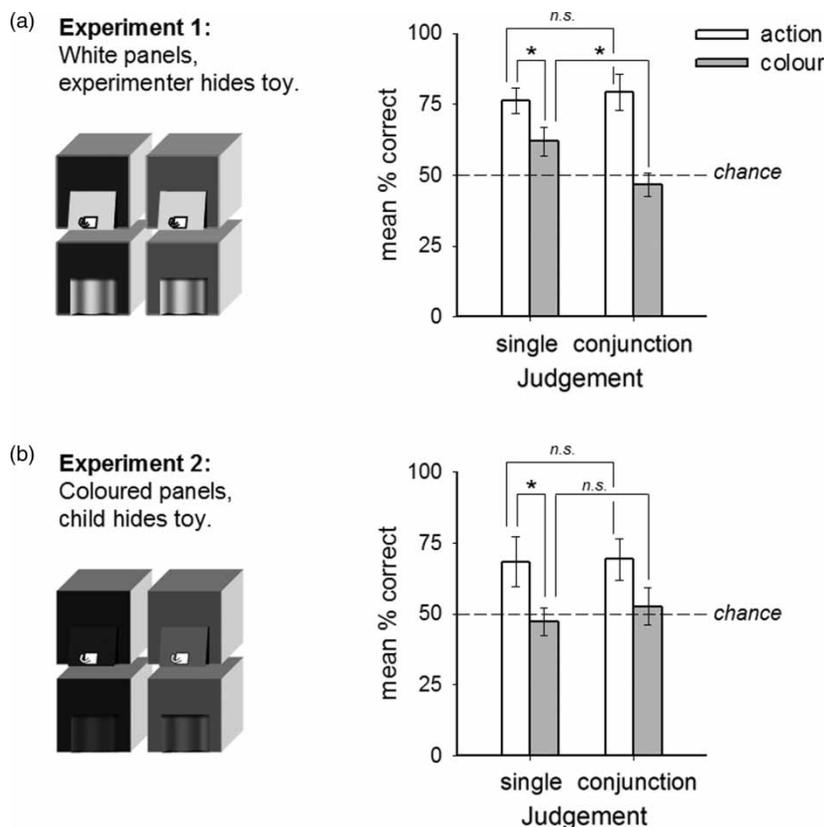


Figure 2. Results from (a) Experiment 1 and (b) Experiment 2. Mean percentage of searches (standard error bars) in single judgements (left) and conjunction judgements (right) correct with respect to action (white bars) and colour (grey bars). The rate of correct search expected by chance is shown. Results of two-tailed paired *t* tests comparing conditions: "*" significant at the 5% level (two-tailed); "n.s." not significant.

To evaluate effects of learning, rates of correct search were analysed for the first three blocks (which were completed by all participants) in ANOVAs with *block* as a within-subjects factor. There was no significant effect of block for single colour, $F(2) = 0.51$, $p > .6$, single action, $F(2) = 0.86$, $p > .4$, conjunction colour, $F(2) = 1.06$, $p > .3$, or conjunction action, $F(2) = 1.46$, $p > .2$, judgements. There was therefore no evidence that incremental learning played a role in children's discriminations for either cue.

Discussion

The baseline rates for single action and colour discriminations provide a measure of how successfully

each of these cues was held in working memory while the target box was out of view and was subsequently used to judge between the correct box and one other. If the "dorsal" and "ventral" visual cues provided, respectively, by action and colour information were maintained and integrated independently for conjunction judgements, the probability of correctly using either cue should remain the same as that in the single condition. This pattern was not found: Instead use of the colour cue fell to chance in conjunction judgements, while use of the action cue remained high. That is, children acted as if they remembered the action but forgot the colour. Given that the initial part of single and conjunction trials did not differ, the contents of children's memory

could not have been different for the two conditions. However, colour was more often used to guide action when it was the only cue relevant at retrieval than when it was one of two relevant cues.

Baseline performance on each of the two discriminations was not matched: Children were significantly better at using the action cue than the colour cue on its own. It is possible, therefore, that the decline in use of colour in this study does not reflect anything special about colour processing, but is a more general effect in which use of the weaker of two cues declines in conjunction judgements. Therefore although the results meet the prediction that colour will be poorly used in conjunction, it is not possible to tell whether this is only a consequence of colour being less well encoded in the first place. In Experiment 2 we sought to achieve a better match in use of the two cues for single judgements.

EXPERIMENT 2

Method

Participants were 10 children 18–24 months old (7 male, mean age 22.0 months, *SD* 1.6 months). We attempted to boost the colour cue by also colouring the panels and curtains of the boxes, on which children act to retrieve the toy. Thus the whole fronts of the boxes were now red and blue, except for the hooks on hook-boxes, which remained white; see Figure 2b. We also changed the procedure so that in the hiding phase, instead of watching the experimenter hide the toy, the child was given the toy and was asked to put it in the target box. It was hoped that interacting with the box would draw children's attention to its appearance. The design and procedure were otherwise the same as those for Experiment 1.

Results

Figure 2b plots results from Experiment 2. Single action judgements were at 68%, significantly above chance, $t(9) = 2.06, p < .05$, one-tailed. However, our change to the procedure did not lead to the

predicted improvement in colour use; in fact, single colour judgements were now at chance, 47%.

In conjunction judgements, 69% of searches were action-correct; this did not differ from the rate for single action judgements; $t(9) = 0.15, p > .8$. As use of colour was already at chance for single judgements, it was not possible to evaluate the prediction that it would fall in conjunction. The rate of colour-correct searches remained at chance (52%), not significantly different to the single colour rate; $t(9) = 0.87, p > .4$.

When single colour and action discriminations from Experiments 1 and 2 were compared, single action discriminations were not significantly different; $t(19) = 0.80, p > .4$, but single colour discriminations were significantly worse; $t(19) = 2.11, p < .05$.

Discussion

Two elements of the design of Experiment 1 were changed: The boxes were made more colourful, and children were asked to hide the toy in the box themselves. It is difficult to see how providing a larger colour cue could have led to a decrease in its use. The results suggest that children's active role in the task was responsible for their even poorer use of colour. Interestingly, doubling children's rate of interaction with the box, so that they executed both the hiding and the retrieval action on every trial, did not produce any improvement in correctly discriminating either the colour or the action cue. On the contrary, it seems that it completely abolished their use of the colour cue.

Children's total inattention to a colour cue that seems very salient to adults is quite surprising. Results from Experiments 1 and 2 show that it is easy for young children to fail to remember and act on colour. These results are consistent with the relative inattention to object colour in looking-time studies with younger children (Wilcox, 1999) and with disregard of colour in spatial orientation tasks with children of this same age (18–24 months; Hermer & Spelke, 1994, 1996).

To evaluate whether these effects arise from differences in the way colours and actions are processed, or whether they just arise when one cue is weaker, Experiment 3 changed the procedure again to improve children's use of colour. It also tested integration for two other surface cues—monochromatic textures and faces—and studied development of the integration of these cues by testing 30–36-month-olds as well as 18–24-month-olds.

EXPERIMENT 3

Method

The fully coloured boxes from Experiment 2 were retained, but the procedure reverted to children watching the experimenter hide the toy. Two further sets of boxes were devised to test whether effects for colour generalize to other “ventral” cues; see Figure 3.

In a “textures” condition, the surface judgement was between patterns of black and white bars and spots. The fronts of two boxes were divided in half vertically with the left half black and the right half white (large texture elements, vertically oriented), while the fronts of the other two boxes had white horizontally elongated spots on a black background (small texture elements, horizontally oriented; Figure 3b); the average brightness of these two patterns was the same. In a “faces” condition, the fronts of boxes were taken up with monochromatic photographs of the faces and torsos of two people, a man and a woman, who (as well as different faces) had different clothes and hair (Figure 3c). In pilot work, children were at chance with face stimuli that were more alike than these. In all three conditions the second cue was a visual action cue (hook vs. curtain), as in Experiments 1–2. The different colour, texture, and face cues took up the whole of the fronts of the boxes, including the panel or curtain; see Figure 3. The left and right edges of “faces” and “textures” boxes were outlined in red. These features on the otherwise monochromatic boxes highlighted the hiding and retrieval places.

To improve sensitivity for detecting differences between conditions, sizes of groups were approximately doubled with respect to Experiments 1 and 2. In total, 122 children were tested. Of these, 6 would not follow the procedure correctly or completed fewer than three blocks, 2 had a strong side bias, and 3 a strong bias for responding to the incorrect cue (same criteria as those for Experiment 1); 111 were retained for analysis.

In the “colours” condition there were 20 children 18–24 months old (mean age 21.4 months, *SD* 2.0 months; 12 male) and 20 children 30–36 months old (mean age 33.3 months, *SD* 1.8 months; 11 male). In the “textures” condition there were 14 children 18–24 months old (mean age 21.4 months, *SD* 2.5 months; 6 male) and 18 children 30–36 months old (mean age 33.5 months, *SD* 1.8 months; 33 male). Testing with the younger age for textures stopped after fewer participants than other conditions as it became clear that children were at chance on the texture discrimination; see Results. In the “faces” condition there were 19 children 18–24 months old (mean age 21.1 months, *SD* 2.0 months; 9 male) and 20 children 30–36 months old (mean age 33.5 months, *SD* 1.5; 11 male).

Results

Figure 4 plots mean percentage of action- and colour-correct searches in single and conjunction judgements by condition (top to bottom) and age (left to right). To summarize, disregard of the surface cue was seen for colours at 18–24 months and for textures at 30–36 months, but not for faces at either age.

Integration of colour and action cues

With fully coloured boxes and the experimenter hiding the toy while the child watched, abilities for the single colour and action discriminations were closely matched (Figure 4a). At 18–24 months mean rates were 67% correct for action and 68% correct for colour; $t(19) = 0.06$, $p > .9$. At 30–36 months they were 70% for both cues; $t(19) = 0.10$, $p > .9$. Use of the action cue did not change in conjunction judgements at either

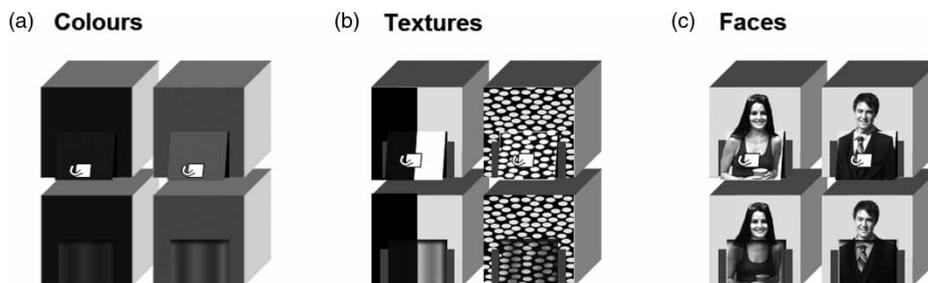


Figure 3. Stimuli for Experiment 3: boxes combining book or curtain retrieval actions with (a) red versus blue colour; (b) "bar" versus "spots" texture; (c) female versus male face and body pictures. In (a) shades of grey are used to illustrate red and blue (the colours used did not have such a large brightness difference).

age; at 18–24 months, $t(19) = 0.33, p > .7$, at 30–36 months, $t(19) = 0.35, p > .7$. By contrast, use of the colour cue fell significantly at 18–24 months, from 68% in single judgements to 57% in conjunction judgements; $t(19) = 2.42, p < .03$. At 30–36 months, however, use of colour in conjunction, 68%, did not differ significantly from its use singly, 70%; $t(19) = 0.50, p > .6$.

These results show that when rates of ability to hold either the colour or the action cue in working memory were very closely matched, based on children's ability to deploy either cue alone in a single judgement, at 18–24 months the colour cue but not the action cue was disregarded in conjunction judgements. So when required to integrate both visual action and surface features of an object, children tended to disregard colour, even though this surface feature is salient when judged alone. This phenomenon seems to be transient, as it is no longer in evidence by 30–36 months, when ability for single colour and action judgements seems to translate straightforwardly into ability for conjunction judgements.

Integration of monochromatic texture and action cues

Figure 4b plots results from children tested with texture as the surface cue. The 18–24-month-olds were not above chance at discriminating boxes by texture even in single judgements, and their mean rate, 46%, was significantly below their rate for the action cue, 71%; $t(13) = 2.93, p < .02$. Owing to this floor effect, use of textures could not fall

further for conjunction judgements. It remained similar at 47%; $t(13) = 0.19, p > .8$. The prediction for a decline in use of the surface cue therefore could not be evaluated at this age. At the same time, use of the action cue in conjunction did not change significantly; $t(13) = 0.91, p > .3$.

At 30–36 months children were adept at distinguishing boxes by texture (see Figure 4b), averaging 67% correct in single texture judgements, not significantly different from the 72% correct for single action judgements; $t(17) = 0.88, p > .3$. In conjunction judgements use of the action cue remained no different to its use singly; $t(17) = 0.00, p = 1.00$. By contrast, in conjunction judgements use of the texture cue fell to 53%, a rate significantly below the single rate of 67%; $t(18) = 2.45, p < .03$.

These results indicate that monochromatic texture is a surface cue that is poorly used to code location at 18–24 months. By 30–36 months the texture cue was used as successfully as the action cue in single judgements, but in conjunction judgements with the action cue, use of the texture cue fell to chance. This contrasts with the surface cue provided by colour, which did not fall in conjunction with the action cue at this age (Figure 4a).

Integration of faces and action cues

At both 18–24 and 30–36 months, children tested with the face–action boxes showed similar ability to discriminate boxes by the face and body pictures as by opening actions in single judgements

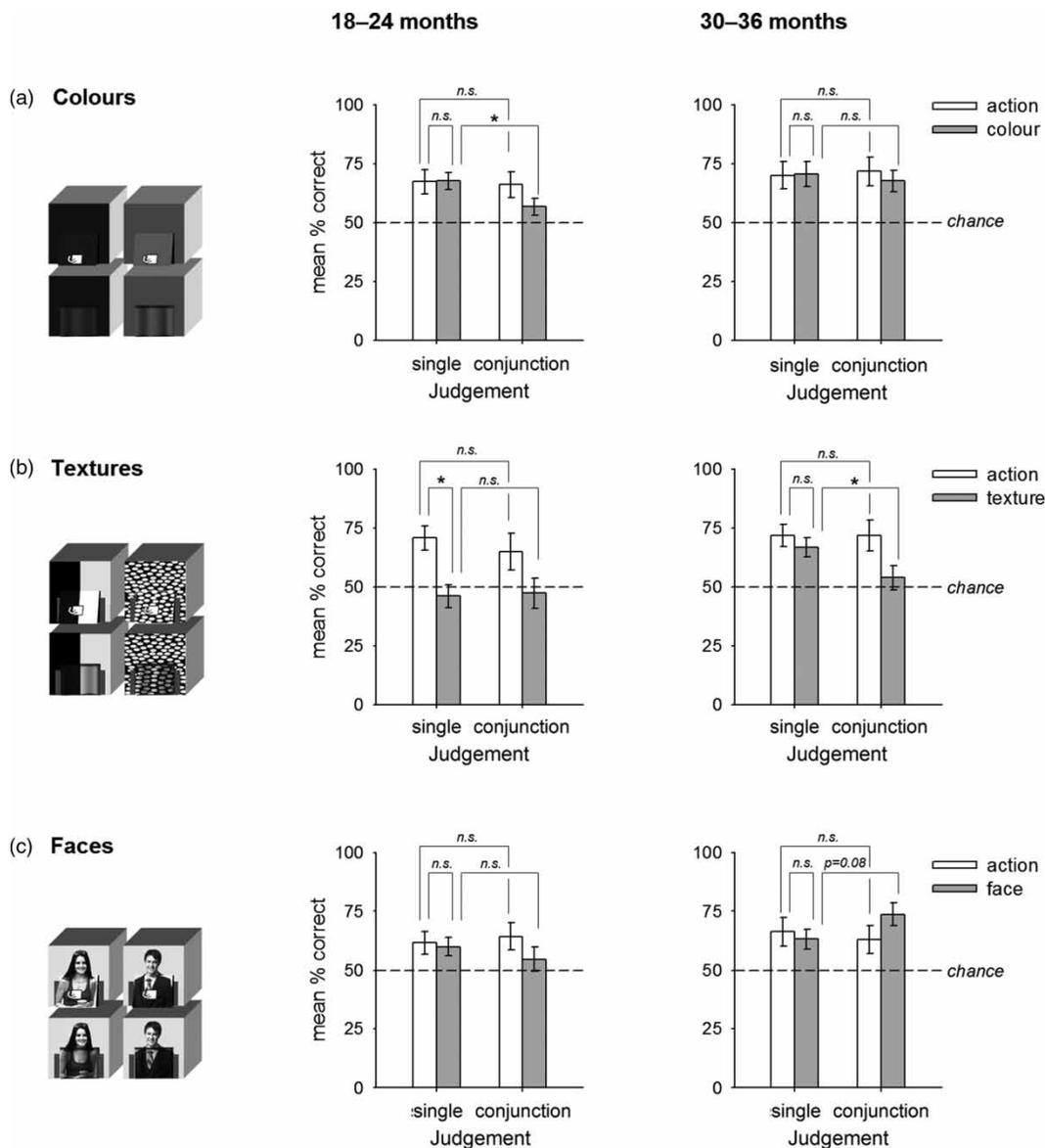


Figure 4. Results from Experiment 3: mean percentage correct searches (standard error bars) with (a) colour, (b) texture, and (c) face stimuli, at 18–24 months (left) and 30–36 months (right). In each plot, single judgements (left) and conjunction judgements (right) are shown for the action cue (white bars) and the surface (colour, texture, or face) cue (grey bars). Results of two-tailed paired t tests comparing conditions: “*” significant at the 5% level (two-tailed); “n.s.” not significant.

(Figure 4c). At 18–24 months, faces (60%) did not differ from actions (62%); $t(18) = 0.24, p > .8$. At 30–36 months, faces (63%) and actions (66%) again did not differ; $t(19) = 0.54, p > .5$. As

before, for conjunction judgements use of the action cue did not decline significantly at either age; at 18–24 months, $t(18) = 0.43, p > .6$; at 30–36 months, $t(19) = 0.61, p > .5$.

Neither age showed a significant decline in use of the face cue in conjunction with action. At 18–24 months, use of the face cue fell nonsignificantly from 60% to 55%; $t(18) = 0.74, p > .4$. Counter to our prediction, at 30–36 months use of the face cue rose considerably for conjunction judgements, from 63% to 74%, a difference that approached statistical significance; $t(19) = 1.86, p = .078$.

Importantly, this result shows that at the ages studied the “disregard” effect does not generalize to all visual cues that are surface and not “affordance” based: It does not extend from colours and textures to the more complex “ventral” cue provided by images of faces. There are several reasons why faces might be processed differently and therefore differently integrated with action; see Discussion. It is also possible that as particularly attention-grabbing stimuli, the faces situated above the panel with the opening action drew attention away from the action (i.e., that children fixated the face rather than the panel). This could explain the somewhat lower rate of single action-correct judgements at both ages relative to the two other conditions.

Differences in integration by cue and age

The above results show different patterns of cue integration as a function of surface cue and age. For example, disregard of colour cues in conjunction judgements was seen at 18–24 but not 30–36 months, an age difference. At 30–36 months, disregard of surface cues was seen for textures but not colours or faces, a cue difference. To evaluate whether there were overall differences in integration as a function of cue and age, results were entered into a mixed ANOVA with between-subjects factors *age* (18–24 or 30–36) and *condition* (colours, textures, or faces), and within-subjects factors *cue* (surface or action) and *judgement* (single or conjunction).

There was a main effect of Age, corresponding to an overall advantage for older participants, $F(1) = 5.79, p < .02$, a main effect of Cue, corresponding to an overall advantage for action over surface cues, $F(1, 105) = 8.78, p < .01$, but no main effect of Judgement, showing that single and conjunction judgements did not differ

overall, $F(1, 105) = 1.83, p > .1$. There was a significant Condition \times Cue interaction; $F(1, 105) = 4.09, p < .03$, which corresponds to the result that whether the surface cue was disadvantaged with respect to the action cue depended on the condition—that is, on whether the surface cues were colours, textures, or faces.

The main effect of Cue and the Cue \times Condition interaction reflect the choice of cues in the design, in that if different visual features were chosen, overall differences between surface and action cues (and differences in this difference by condition) would change. Evidence for differential integration of surface and action cues in single and conjunction judgements would come from an interaction including the *judgement* factor. There was such an interaction, for Age \times Condition \times Cue \times Judgement; $F(2, 105) = 3.30, p < .05$. One way to describe this interaction is that how differences between single and conjunction judgements for surface and action cues varied as a function of cue pair (colour–action, texture–action, or face–action) was moderated by age. No other interactions were significant; in particular, there was no evidence either for a Condition \times Cue \times Judgement effect unmoderated by age ($p > .4$), nor for a Cue \times Judgement \times Age effect unmoderated by condition ($p > .7$). In summary, the ANOVA shows uneven integration for visual cues in development, changing with the nature of the cue and with age. This is in agreement with the preceding analyses of individual conditions, which show differential patterns of integration by cue and age.

Effects of learning

Maintaining the visual features that distinguish the correct box has been described as a working-memory task. However, as each child saw the toy hidden in the same box throughout the study, incremental learning for these features could contribute to performance. The rationale for keeping the boxes the same throughout was not to build up an associative response (which is unlikely given the relatively small number of trials), but to avoid proactive memory interference. However, if incremental learning were an

important factor, then children's deficit in remembering colours and textures might be in associative (stimulus-response) learning, rather than in working memory. It could also be that differential rates of incremental learning for surface and action cues account for the overall asymmetries in using them.

To evaluate to what degree incremental learning contributed to behaviour, scores were analysed by block. An ANOVA including a linear trend term was carried out for each score with within-subjects factor *block* (1-3, as not all completed a fourth block). In total 24 ANOVAs were carried out, one for each measure plotted in Figure 3; only those that showed a significant effect of block are reported here. There was a significant effect of block, corresponding to improving performance for just one cue and condition: conjunction judgements for the action cue in 30-36-month-olds tested on textures; linear F for block = 4.86, $p < .05$. There were three significant effects of block corresponding to decreasing performance: for single judgements of colour in 30-36-month-olds tested on colour (linear F = 4.75, $p < .05$) and conjunction judgements of action in the same group (linear F = 5.15, $p < .04$), and for single judgements of faces in 30-36-month-olds (linear F = 5.15, $p < .04$).

These results show very little evidence for a contribution from incremental learning to the task. On the contrary, effects of block more often showed decreasing performance over the course of the study. After repeated exposure to the target box, children were not, on the whole, better able to discriminate it; instead, presumably decreasing interest in the task tended to make discriminations worse.

Differences between the "hook" and "curtain" actions

In general children tended to prefer the hook action; both children excluded for a bias towards the incorrect action had a bias towards hooks. Among those retained for analysis, there was significantly better "single action" performance for children whose target was the hook on the colour-action condition at 18-24 months (80% vs. 52%); $t(18) = 3.42$, $p < .01$, and on the

face-action condition at 18-24 months (74% vs. 51%); $t(17) = 2.70$, $p < .02$. In other conditions and age groups differences in single action discriminations between "hook" and "curtain" participants were not significant.

These results suggest that for young children, the hooks were an appealing stimulus irrespective of their role in coding where the object is hidden. Insofar as the hooks attracted responses for this extraneous reason, ability to remember the "curtain" cue was underestimated (as participants remembering the curtain may nevertheless open a hook), while ability to remember the "hook" cue was overestimated (as participants with no representation in memory may arbitrarily choose the hook). These opposing biases are averaged in the overall scores plotted in Figure 4 and are reported in the main analysis.

To check whether "disregard of colour at 18-24 months" is moderated by the significant difference in action discrimination between participants assigned to "hook" and "curtain" targets, the analysis was repeated separately for these subgroups. The 18-24-month-olds in the colour-action condition whose target was the hook were correct on colour on 64% of single judgements and 59% of conjunction judgements, showing a decline in use of colour in the same direction as the result for the whole group, although not statistically significant, $t(10) = 0.97$, $p > .3$; it should be noted that the reduction in participant numbers reduces the test's sensitivity). Those assigned to the curtain were correct on colour on 72% of single judgements and 53% of conjunction judgements, showing a significant decline in use of colour, $t(8) = 2.45$, $p < .05$. Results from both subgroups are consistent with the main result, but it is interesting that those participants assigned to the more difficult action showed the strongest disregard of the nonaction cue (colour) in conjunction judgements.

GENERAL DISCUSSION

The present studies showed a set of asymmetries in young children's integration of "perception" and

“action” cues. When judging surface properties of objects at the same time as the objects’ affordances for action, children selectively disregarded surface cues provided by colour and texture. The same did not occur for the surface stimuli provided by face and body pictures. Although these differ in many ways from the low-level colour and texture stimuli used in the other conditions (see below), this result provides a limiting case for the phenomenon, showing that it does not apply to all conjunctions of action and “surface” cues.

Results from all conditions of Experiment 3 analysed together show that there were differential patterns of integration for surface and action cues as functions of both cue and age. It is important to note that in those conditions of Experiment 3 that showed selective disregard of colour and texture in conjunction judgements, discriminations by colour or texture alone were well above chance, well below ceiling, and closely matched to discrimination by the action cue. The decline in ability to use colour or texture in conjunction cannot be accounted for by a poorer initial encoding for it. Rather, there is evidence that surface and action cues were held with similar accuracy in working memory, but use of the surface cue was less accurate at the response stage in judgements that required the use of both cues.

Experiments 1 and 2 also showed that relative to affordance for action, colour was apt to be poorly used as a cue for finding a hidden object. Even with bright and (to adults) highly distinctive red and blue coloured boxes, use of colour was low when the part of the box where hidden toys were retrieved was not also coloured (Experiment 1), or when children carried out both the hiding and the retrieval action (Experiment 2).

These results are consistent with those from looking-time measures at younger ages, which show an initial predominance of spatial over surface information for individuating objects after a delay (Wilcox, 1999; Xu & Carey, 1996) and difficulty maintaining both “ventral” and “dorsal” information about occluded objects (Mareschal & Johnson, 2003). The present results extend these findings, showing uneven

integration for colours to at least 18–24 months and for monochromatic textures to at least 30–36 months. In adults and primates, prefrontal cortex has a crucial role in integrating dorsal and ventral-stream visual information for action (Rao et al., 1997; Rossetti & Pisella, 2002) and in maintaining visual information in working memory (Mohr et al., 2006; Munk et al., 2002). The immaturities of visual cognition seen in the present task therefore suggest an uneven development of integration between the networks processing visual information for action through the first and second years of life. The dissociations between colour, which was disregarded at 18–24 but not at 30–36 months, texture, which was disregarded at 30–36 months, and faces, which were not disregarded at either age, suggest that the developmental changes in the present study may not be best described in terms of the dorsal and ventral streams as a whole, but at the level of specific functions within each stream.

The flat images of faces that we used may have been retained in conjunction judgements as faces have a central role in social interaction: Consistent with their importance for the child, faces are differentiated from other stimuli from birth (Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). However, discrimination by faces alone (“single judgement”) was not better than by colour alone; indeed at both ages the trend was for single face judgements to be worse (see Figure 4). Therefore if faces show a different pattern to colour or texture on the present task, it is not because they were just a more salient cue for search overall. Rather, the difference seems to arise in the integration process tested in the conjunction judgement conditions.

The present disregard of colour in a desktop search task shows that failures to use colour cues to find a hidden object do not only occur when children are disoriented (Hermer & Spelke, 1994, 1996). The disregard of colour reported in reorientation tasks may represent a more general phenomenon in visucognitive development, resulting from difficulties with recruiting perceptual surface cues such as colour and texture to guide action. Hermer and Spelke argued that in

their reorientation task, the developmental change enabling reorientation using colour was the acquisition of spatial language—allowing a location to be coded, for example, as “left of the blue wall” (Hermer-Vazquez, Moffet, & Munkholm, 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999; but see Ratliff & Newcombe, 2008). In the present task, it would be possible to use language to bind visual features in a phrase—for example, coding that a target was the “blue box with a hook”. It is unlikely that many of our participants, all aged 36 months or less, could reliably code red and blue colour in words (Pitchford & Mullen, 2002) and less likely still that they could code a conjunction of colour and action. Some participants might have coded “man” versus “woman” (if not conjunctions of these with action) in the “faces” condition. The extent to which language development might contribute to coding conjunctions of visual features in working memory at this age remains an interesting question for further research (for related work with older children, see Dessalegn & Landau, in press).

Ability to discriminate the boxes along the relevant dimensions may also be linked to the development of categorization. Young children’s ability to represent complex objects in terms of different underlying dimensions is limited (Smith, 1984), and the difficulties in conjunction (four box) judgements in the present task may be in categorizing the boxes according to both dimensions (e.g., colour and action). Children have long been reported to categorize objects earlier by shape than by colour (e.g., Brian & Goodenough, 1929; Kagan & Lemkin, 1961), which is consistent with their difficulties in discriminating by colour, as opposed to the shape signalling the opening action, in the present studies.

Although the target set of visual features remained the same throughout the study for each child, analysis of performance by block showed no evidence that incremental learning, consistent with the building up of an associative response, contributed to children’s discrimination ability. This supports our understanding of the study as a working-memory task. In light of our finding that performance on the task did not improve as the

study progressed, future studies could check whether varying the target from trial to trial might serve better to maintain interest in the task. Some groups showed a significant bias towards the hook action relative to the curtain action. In follow-up studies it would be ideal to find two visually distinctive actions that do not differ in how intrinsically attractive they are to perform.

The present study bears on the real-life problem of rapidly integrating many different cues to guide an action. The broader question is how cues of different kinds are optimally weighted and integrated. Results from this study show that in young children’s working memory, some cues win out over others. With development, visual cue integration improves. An important question is the degree to which children’s failures to integrate colour and texture cues with visual action cues depends on their making action responses to the stimuli. In a future study, participants may “search” boxes with visual action differences without executing the relevant action, by using a pointer instead. A related question is whether conjunction judgements for two surface features will show a disregard of either cue. It will also be interesting to assess cue combination in adults using a directly comparable task.

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