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Semantic congruency and the (reversed) Colavita effect in children and adults

Claudia Wille & Mirjam Ebersbach

University of Kassel

Corresponding author: Claudia Wille, Department of Psychology, University of Kassel, Holländische Str. 36-38, 34127 Kassel, Germany; e-mail: claudia.wille@uni-kassel.de, phone: ++49 561 804 7522

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Sensory integration as a functional principle of the human brain enables a meaningful engagement in the environment by assembling modality-specific information into a unified and coherent perception (cf., Calvert, Spence, & Stein, 2004; Spence & Driver, 2004). Nevertheless, one sensory system often dominates another one when multiple sensory systems are concurrently stimulated. A prominent example for sensory dominance is the ventriloquist effect: The visually perceived position of a sound source dominates the auditorily perceived position (Howard, Craske, & Templeton, 1966; Slutsky & Recanzone, 2001). In fact, research on sensory integration suggests that vision often biases the processing not only of the auditory system but also of the tactile and proprioceptive system (Botvinick & Cohen, 1999; Farnè, Pavani, Meneghello, & Làdavas, 2000; Gallace & Spence, 2005; Hartcher-O'Brien, Gallace, Krings, Koppen, & Spence, 2008). Thus, at least for adults, visual input seems to be more influential than input from other sensory modalities (but see Alais & Burr, 2004).

Another striking example of visual dominance is the Colavita effect (Colavita, 1974). When presented with bimodal stimuli consisting of an auditory and a visual component (e.g., a 400 Hz tone and a visual angle), adults often claim that they have only perceived a visual stimulus while ignoring the auditory component. Apparently, the visual dominance of adults is strong enough to overshadow the awareness for an auditory input when being presented with synchronous bimodal stimuli. Over the years, a vast number of studies have been conducted to further examine this phenomenon, and in nearly all of the studies robust effects in favor of the visual input were shown (e.g., Koppen, Levitan, & Spence, 2009; Sinnett, Spence, & Soto-Faraco, 2007). Although effect sizes varied across studies and could be systematically reduced by some designs (Sinnett et al., 2007), the Colavita effect in adults could not be reversed in terms of auditory dominance over the visual system (for a review see Spence, Parise, & Chen, 2012).

Posner, Nissen, and Klein (1976) attempted to explain the underlying conditions of visual dominance in adulthood by stating that visual stimuli are not as automatically attention-capturing as stimuli presented in other modalities, such as auditory stimuli. Instead, people have to actively focus their attention towards a visual stimulus, which requires cognitive resources and diminishes the attention to stimuli presented in other modalities. The influence of attentional factors on sensory dominance has been recently supported by Sinnett et al. (2007).

Interestingly, the dominance of visual perception does not seem to be innate, as there is evidence that children´s information processing is dominated by the auditory system (see Lewkowicz, 1988a, 1988b; Robinson & Sloutsky, 2004; Sloutsky & Napolitano, 2003), but as research has rarely extended beyond 4-year-olds, several questions remain unanswered. Given a visual dominance in adults and an auditory dominance in 4-year-olds, obviously a change in modality dominance occurs in the course of development.

So far, to our knowledge there is only one study examining the developmental trajectory of sensory dominance across older children (i.e., 6-7, 9-10, 11-12 years of age) and adults using the same procedure and materials for all age groups (Nava & Pavani, 2012). Based on the design used by Colavita (1974), Nava and Pavani could show a switch from auditory dominance in 6- to 7-year-olds towards visual dominance in 9- to 10-year-olds. Children were presented with simple lights and sounds, either separately or simultaneously, and were asked whether they perceived a single auditory, visual, or a bimodal stimulus. In the bimodal condition, older children and adults often ignored the auditory component by indicating that they had only perceived a visual stimulus (Colavita effect), whereas younger children missed far more often the visual component of bimodal stimuli suggesting an auditory dominance (reversed Colavita effect).

In the study of Nava and Pavani (2012), auditory and visual components of bimodal stimuli were synchronously presented at the same spatial location, yielding spatial and temporal congruency. In the current study, we additionally examined the effect of semantic congruency on sensory dominance, which is adapted from the study of Koppen, Alsius, and Spence (2008) with adults. Thus, instead of simple lights and sounds, semantically meaningful stimuli were presented to participants of different age groups.

Our main questions were: Can effects of sensory dominance in children, as demonstrated by means of simple stimuli (Nava & Pavani, 2012), be extended to the processing of complex and meaningful stimuli? If these dominance effects are a robust empirical phenomenon, one should expect them to emerge even if more realistic stimuli are used.

Furthermore, we were interested in whether the manipulation of semantic congruency affects the magnitude of sensory dominance effects in different age groups. Multisensory stimuli of a single object or event usually do not only share temporal and spatial attributes, but also certain semantic features that facilitate their identification (Laurienti, Kraft, Maldjian, Burdette, & Wallace, 2004). For instance, a barking four-legged-animal is labeled as a dog. In contrast, semantic congruency is lacking when being presented with a ringing four-legged animal. Whereas the “semantic mismatch” in semantically incongruent trials should contribute to a better detection or “pop-out” of both stimuli components, there should be a facilitating effect regarding sensory dominance in the semantically congruent trials: In congruent trials, older children and adults – usually exhibiting a visual dominance – should show a stronger tendency to overhear the auditory component of a bimodal stimulus combination, as the auditory components contain only “redundant information”. This should also be the case for younger children but, due to their auditory dominance, they should neglect the visual component: In congruent trials, they should show a stronger tendency to overlook the visual component of a bimodal stimulus combination compared to incongruent trials. Thus, sensory dominance should become more evident in semantically congruent than in incongruent trials.

Three experiments were conducted, in which stimulus congruency was manipulated. Additionally, the number of bimodal trials was varied between Experiment 1 and 2 in order to examine whether the relative frequency of bimodal stimuli has an impact on sensory dominance. In Experiment 3, we were examining whether the absence of color information could remove visual dominance in older children and adults.

Experiment 1

Methods

Sample. Participants were 27 6-year-olds (*M* = 6.4 years, *SD* = 0.5; 13 males, 14 females attending preschool or first grade), 30 9-year-olds (*M* = 8.9 years, *SD* = 0.8; 13 males, 17 females attending second or third grade), and 28 adults (*M* = 25.9 years, *SD* = 5.8; 12 males, 16 females). Children were recruited from local schools and nurseries, after their parents had signed a consent form. The adults were staff and students from university of the same medium-sized city being unfamiliar with the aim of the experiment.

Stimuli and procedure. Stimulus programming, presentation, and response collection were carried out using the program Inquisit. Visual stimuli consisted of four colored, schematic images (i.e., a brown dog, a cow with brown patches, a red telephone, a golden bell, all measuring 12 x 9 cm) presented at the center of a white-background monitor measuring 42.6 cm x 32.7 cm. Auditory stimuli consisted of four sounds (i.e., the bark of a dog, the moo of a cow, the ring of a phone, the toll of a bell) presented on headphones at 65 db. Each visual and auditory stimulus was either presented alone (unimodal condition: auditory-only and visual-only trials) or a visual and an auditory stimulus were presented together (bimodal condition). The bimodal condition consisted of semantically congruent and incongruent trials. In incongruent trials, all possible combinations of visual and auditory stimuli were presented.

Participants were instructed to press one button (marked by the symbol of a picture frame) in response to a single visual stimulus, another button in response to a single auditory stimulus (marked by the symbol of a note) or a third button whenever they perceived a visual and an auditory stimulus simultaneously (marked by the symbol of a picture frame with a note in it). The experiment started with 12 training trials presented in random order, among them 3 semantically congruent trials, 3 semantically incongruent trials, 3 auditory-only and 3 visual-only trials. The following 96 experimental trials consisted of 32 visual-only trials, 32 auditory-only trials, 16 semantically incongruent trials and 16 semantically congruent trials, which were presented in random order, too. An experimental session lasted about 10 min. Each trial started with the onset of the target presented for maximally 500 ms. If the participant did not respond within this period, the target disappeared, followed by a white screen (which was consistently presented in the auditory-only trials). A response was mandatory in order to continue with the experiment. If a participant did not give a response after five seconds, he or she was asked to remember what kind of stimuli was presented and to guess, if necessary (cf., Robinson & Sloutsky, 2004). After the response and an inter-stimulus interval of 750 ms, the next target emerged. No feedback was provided except for the training trials, in which the experimenter said “true” or “false”. Participants were instructed to react as fast and as accurate as possible. After completing the experiment, adults were provided with information about the aim of the study and children received an attendance certificate and stickers.

Results

One 6-year-old child was excluded from the analyses as he made more than 50 % errors in the unimodal condition. For a summary of the mean error rates of each age group in the bimodal condition, see Table 1. The Colavita effect is defined by significantly more visual-only responses (in the following called “visual errors”) than auditory-only responses (in the following called “auditory errors”) in bimodal trials (Koppen et al., 2008). A “reversed Colavita effect” in terms of an auditory dominance would be defined, in turn, by significantly more auditory errors than visual errors in bimodal trials. In order to check whether there were more visual or auditory errors in the different age groups and semantic conditions, an ANOVA with repeated measures on the within-subjects variables semantic congruency (congruent versus incongruent trials), error type (visual versus auditory errors in bimodal trials), and the between-subjects variable age group (6-year-olds, 9-year-olds, adults) was conducted. The number of visual versus auditory errors in bimodal trials served as dependent measures.

There was no significant main effect of error type, $p = .45$, but significant main effects of age group, $F(2, 82) = 7.12$, $p = .001$, $\eta^2 = .15$, and congruency, $F(1, 82) = 32.04$, $p < .001$, $\eta^2 = .28$. A significant interaction emerged between error type and age group, $F(2, 82) = 9.18$, $p < .001$, $\eta^2 = .18$. To specify this effect, an ANOVA with repeated measures was conducted separately for each age group.

Six-year-olds made significantly more auditory errors than visual errors in the bimodal condition, $F(1, 26) = 5.60$, $p = .026$, $\eta^2 = .18$, suggesting auditory dominance. Furthermore, they made significantly more errors in semantically congruent trials than in incongruent trials, $F(1, 26) = 12.77$, $p = .001$, $\eta^2 = .33$. Contrary to our prediction, no significant interaction between error type and congruency emerged, $p = .16$, suggesting that the auditory dominance of 6-year-olds was not affected by semantic congruency between the auditory and visual components of a bimodal stimulus combination.

Nine-year-olds, in contrast, made significantly more visual errors than auditory errors in the bimodal condition, $F(1, 29) = 7.55$, $p = .010$, $\eta^2 = .21$, suggesting visual dominance. Furthermore, they made significantly more errors in semantically congruent trials compared to incongruent trials, $F(1, 29) = 14.97$, $p =. 001$, $\eta^2 = .34$. As expected, a significant interaction between error type and congruency was revealed, $F(1, 29) = 5.01$, $p = .033$, $\eta^2 = .15$. This was attributable to significantly more visual errors than auditory errors in semantically congruent trials, $t(29) = 2.72$, $p = .011$, $d = .63$, whereas in incongruent trials no significant difference was revealed, $p = .33$. Thus, the visual dominance of 9-year-olds occurred only under semantic congruency.

Similar to 9-year-olds, adults made significantly more visual errors than auditory errors in the bimodal condition, suggesting visual dominance, $F(1, 27) = 6.42$, $p = .017$, $\eta^2 = .19$. Similar to the two groups of children, they made significantly more errors in semantically congruent trials than in incongruent trials, $F(1, 27) = 5.70$, $p = .024$, $\eta^2 = .17$, but no significant interaction between error type and congruency was revealed, $p = .25$. This suggests that the visual dominance of adults was not affected by semantic congruency.

As the assignment of response keys was not counterbalanced in the present study, additional analyses were conducted in order to check whether sensory dominance was no result of different response biases in each age group. A response bias could be identified in the unimodal condition as reflected by an unequal distribution of visual and auditory errors due to a “preferred key”. However, paired *t*-tests for each age group (Bonferroni corrected) revealed no significant differences between auditory and visual errors (*p*s > .05).

Table 1

Mean error rates (in %) for the bimodal condition in total and separately for congruent and incongruent trials

	6-year-olds		9-year-olds		Adults	
Mean error rate in the bimodal condition	17.1	(10.2)	10.10	(6.9)	9.49	(7.5)
Auditory errors	10.8	(9.3)	3.13	(3.1)	3.57	(5.8)
Visual errors	6.4	(3.6)	6.98	(6.6)	6.03	(2.9)
Mean error rate in incongruent trials	13.2	(7.6)	5.62	(7.0)	6.92	(7.1)
Auditory errors	7.9	(8.2)	2.29	(3.8)	2.90	(4.0)
Visual errors	5.3	(3.7)	3.33	(5.1)	4.02	(5.2)
Mean error rate in congruent trials	21.1	(14.7)	14.59	(11.2)	12.28	(11.6)
Auditory errors	13.7	(12.1)	3.96	(6.5)	4.24	(5.1)
Visual errors	7.4	(6.7)	10.63	(5.3)	8.04	(9.3)

Note. Standard deviations in parentheses.

Discussion

Experiment 1 confirmed a robust visual dominance in adults (i.e., Colavita effect, Colavita, 1974), which was not affected by semantic congruency (for similar results with adults, see Koppen et al., 2008). Furthermore, the results suggest that visual dominance of 9-year-olds and auditory dominance of 6-year-olds is not restricted to simple lights and sounds (Nava & Pavani, 2012), but can be extended to the processing of complex, semantic stimuli. Except for 9-year-olds, sensory dominance did not seem to be affected by semantic congruency. It is important to note, however, that congruency did affect performance: As all age groups made significantly more errors in semantically congruent compared to incongruent trials, congruency obviously restrains the processing of bimodal stimuli. The underlying factor for the better performance in incongruent trials might be the presence of a semantic mismatch that could have provided participants with a cue that a bimodal target had, in fact, been presented.

Experiment 2 served to check the robustness of the findings by manipulating the relative frequency of bimodal stimuli. In Experiment 1, twice as many unimodal than bimodal stimuli were presented. Thus, the question emerged whether the bimodal stimulus frequency has an effect on accuracy and whether sensory dominance might be modulated by changing this frequency. For adults, a visual dominance effect emerged whenever bimodal stimuli were presented in 60% or less of all trials, but this effect declined when bimodal stimuli were presented more frequently (Koppen & Spence, 2007). This suggests that response-related factors are likely to play a role: The higher the probability of occurrence, the better the monitoring of bimodal stimuli and the preparedness to press the bimodal button. This, in turn, might contribute to a higher accuracy in the bimodal condition and a decline of the Colavita effect. Based on the findings of Koppen and Spence (2007), an equalized frequency of unimodal and bimodal stimuli should not affect the magnitude of the sensory dominance effect in adults, but potentially in children.

Experiment 2

Methods

Sample. Participants were 19 6-year-olds (*M* = 6.5 years, *SD* = 0.6; 9 males, 10 females attending preschool or first grade), 17 9-year-olds (*M* = 9.1 years, *SD* = 0.7; 7 males, 10 females attending second or third grade) and 23 adults (*M* = 27.6 years, *SD* = 10.4; 11 males, 12 females). Subjects were unfamiliar with the aim of the study. The samples of the current experiment were comparable concerning mean age, gender distribution, and socioeconomic status to the samples of the preceding experiment.

Stimuli and procedure. Stimuli and procedure were identical to Experiment 1 with the sole exception that an equal number of unimodal and bimodal stimuli were presented (i.e., 64 unimodal trials: 32 visual-only, 32 auditory-only trials; 64 bimodal trials: 32 semantically incongruent, 32 semantically congruent trials).

Results

For a summary of the mean error rates in the bimodal condition, see Table 2. In order to check whether there were more visual or auditory errors in the different age groups and semantic conditions, an ANOVA with repeated measures on the within-subjects variables semantic congruency (congruent versus incongruent trials), error type (visual versus auditory errors in bimodal trials), and the between-subjects variable age group (6-year-olds, 9-year-olds, adults) was conducted. The number of visual versus auditory errors in bimodal trials served as dependent measures. There were significant main effects of age group, $F(2, 56) = 9.76$, $p < .001$, $\eta^2 = .26$, and congruency, $F(1, 56) = 19.76$, $p < .001$, $\eta^2 = .26$. As in Experiment 1, a significant interaction emerged between error type and age group, $F(2, 56) = 9.77$, $p < .001$, $\eta^2 = .26$. To specify the effects of congruency on error type, an ANOVA with repeated measures was conducted for each group separately. The results were largely comparable with Experiment 1.

Six-year-olds made significantly more auditory errors than visual errors in the bimodal condition, suggesting auditory dominance, $F(1, 18) = 6.72$, $p = .018$, $\eta^2 = .27$. Furthermore, they made significantly more errors in semantically congruent trials than in incongruent trials, *F*(1, 18) = 5.11, $p = .036$, $\eta^2 = .22$, and a marginally significant interaction between error-type and congruency was revealed, $p = .08$.

Nine-year-olds made significantly more visual errors than auditory errors in the bimodal condition, suggesting visual dominance, *F*(1, 16) = 4.84, $p = .043$, $\eta^2 = .23$. Furthermore, they made significantly more errors in semantically congruent trials compared to incongruent trials, *F*(1, 16) = 18.00, $p =. 001$, $\eta^2 = .53$. In line with Experiment 1 and our predictions, a significant interaction between error type and congruency was revealed, *F*(1, 16) = 5.12, $p = .038$, $\eta^2 = .24$. This was attributable to significant more visual errors than auditory errors in the semantically congruent trials, *t*(16) = 2.64, $p = .018$, $d = .85$, whereas in the incongruent trials no significant difference was revealed, $p = .77$. Thus, visual dominance of 9-year-olds occurred only under semantic congruency.

Adults, too, made significantly more visual errors than auditory errors in the bimodal condition, suggesting visual dominance, *F*(1, 22) = 7.91, $p = .010$, $\eta^2 = .26$. Similar to the two groups of children, they exhibited significantly more errors in semantically congruent trials than in incongruent trials, *F*(1, 22) = 6.30, $p = .020$, $\eta^2 = .22$. No significant interaction between error type and congruency was revealed, $p = .87$. As in Experiment 1, a response bias could be ruled out.

Table 2

Mean error rates (in percentage) for the bimodal condition in total and separately for congruent and incongruent trials

	6-year-olds		9-year-olds		Adults	
Mean error rate in the bimodal condition	7.32	(5.4)	4.14	(2.8)	2.38	(2.1)
Auditory errors	4.69	(3.9)	1.38	(1.4)	0.68	(0.9)
Visual errors	2.63	(2.3)	2.76	(2.2)	1.70	(1.7)
Mean error rate in incongruent trials	5.60	(5.2)	2.76	(2.4)	1.49	(2.1)
Auditory errors	3.13	(4.4)	1.29	(1.6)	0.27	(0.1)
Visual errors	2.47	(2.9)	1.47	(1.9)	1.22	(1.8)
Mean error rate in congruent trials	9.05	(7.3)	5.51	(3.6)	3.26	(3.2)
Auditory errors	6.25	(4.9)	1.47	(2.0)	1.09	(1.5)
Visual errors	2.80	(3.3)	4.04	(3.3)	2.17	(2.7)

Note. Standard deviations in parentheses.

Further analyses were conducted in order to examine whether the higher frequency of bimodal trials in Experiment 2 affected the magnitude of the sensory dominance effects compared to Experiment 1. The magnitude of a sensory dominance effect can be conceived as the relative difference between auditory and visual errors on bimodal trials (Koppen et al., 2008). Thus, the difference between auditory errors and visual errors on bimodal trials (both in %) was compared between Experiment 1 and Experiment 2. A 3 (age group: 6-year-olds, 9-year-olds, adults) x 2 (Experiment: Experiment 1 versus Experiment 2) ANOVA was conducted with sensory dominance as dependent variable. There was a significant main effect of age, $F(2, 138) = 11.73$, $p < .001$, $\eta^2 = .15$, no significant main effect of experiment, $p = .62$, and no interaction, $p = .16$. Thus, the magnitude of the visual dominance effect in older children and adults, as well as the auditory dominance in younger children did not differ significantly between Experiment 1 and 2. This could be taken as a hint that the additional number of bimodal trials in the current experiment did not affect the magnitude of sensory dominance effects in children and adults.

However, the mean total error rate in the bimodal condition – cumulated across the percentage of visual and auditory errors – was higher in the current experiment than in Experiment 1, suggesting that the higher frequency of bimodal trials might have had an effect on the general accuracy. To test this, a 3 (age group: 6-year-olds, 9-year-olds, adults) x 2 (experiment: Experiment 1 versus Experiment 2) ANOVA with the mean total error rate in the bimodal condition as dependent variable was conducted, revealing significant main effects of age group, $F(2, 138) = 11.03$, $p < .001$, $\eta^2 = .14$, and experiment, $F(1, 138) = 43.40$, $p < .001$, $\eta^2 = .24$, but no significant interaction between age group and experiment, $p = .40$. Thus, all age groups exhibited a higher accuracy in the bimodal condition of the current experiment compared to Experiment 1. This suggests facilitating effects due to the additional number of bimodal trials, even if this suggestion has to be drawn cautiously as two different samples participated in Experiment 1 and 2**.**

Discussion

The results were largely in line with Experiment 1 although the relative frequency of bimodal stimuli was increased. A robust visual dominance effect (Colavita, 1974) was revealed in adults and an auditory dominance effect in 6-year-olds. Both were not affected by semantic congruency, although the interaction among 6-year-olds indicated a tendency for significantly more auditory errors in congruent compared to incongruent trials

Among 9-year-olds, a visual dominance effect occurred only under semantic congruency, which is in line with the findings of Experiment 1.

As predicted, the magnitude of the visual dominance effect in adults was not affected by the higher frequency of bimodal trials in the current experiment compared to Experiment 1. This was also the case for sensory dominance effects in children, suggesting a similar robustness regarding relative bimodal stimulus frequencies. Manipulating the frequency of bimodal trials, however, seemed to have an effect on the general accuracy as all age groups exhibited a smaller mean error rate in the bimodal condition of the current experiment compared to Experiment 1. This suggests that a higher frequency of bimodal stimuli might reduce the error rate in the bimodal condition, but does not have an impact on the magnitude of a sensory dominance effect.

In order to further examine the robustness of sensory dominance effects, a third experiment was conducted, in which color information of the stimuli was manipulated. Color information plays a crucial role in detecting and recognizing objects. For example, in a study of Wurm, Legge, Isenberg, and Luebker (1993), participants had to name food objects presented as grey-scaled or colored images. Reaction times were significantly shorter and accuracy higher in the condition of colored images. Furthermore, shorter reaction times for colored stimuli were related to objects' prototypicality but not to their color diagnosticity[1]. Thus, it was concluded that color does improve object recognition and that the underlying mechanism is probably sensory rather than cognitive in origin (Wurm et al., 1993). Given these premises, removing color information might affect the Colavita effect in a detrimental way: As monochrome images by presenting them in black and white lack salience compared to the colored ones, the privileged processing of visual stimuli (compared to auditory stimuli) could be restrained.We therefore hypothesized that the visual dominance of older children and adults will be reduced or even disappeared, whereas the auditory dominance of younger children should not be affected and still be present.

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[1] Objects vary in the degree to which their colors are "diagnostic" (Biederman & Ju, 1988). Although virtually no object can be recognized on the basis of its color alone, some objects (e.g., a banana) are associated stronger with a particular color than others (e.g., a telephone) (Wurm et al., 1993).

Experiment 3

Methods

Sample. Participants were 18 6-year-olds (*M* = 6.4 years, *SD* = 0.5; 8 males, 10 females attending preschool or first grade), 24 9-year-olds (*M* = 9.1 years, *SD* = 0.9; 10 males, 14 females attending second or third grade), and 20 adults (*M* = 26.5 years, *SD* = 6.8; 7 males, 13 females). Subjects were unfamiliar with the aim of the study. The samples of the current experiment were comparable concerning mean age, gender distribution, and socioeconomic status to the samples of the preceding experiments.

Stimuli and Procedure. Stimuli and procedure were identical to Experiment 2 with the sole exception that visual stimuli were presented in black and white instead of colored images.

Results

For a summary of the mean error rates of each age group in the bimodal condition, see Table 3. Analogous to the preceding experiments, a 3 (age group: 6-year-olds, 9-year-olds, adults) x 2 (error type in bimodal trials: visual errors versus auditory errors) x 2 (semantic congruency: congruent trials versus incongruent trials) ANOVA with repeated measures was conducted. Significant main effects of error type, $F(1, 59) = 4.24$, $p = .044$, $\eta^2 = .07$, age group, $F(2, 59) = 25.34$, $p < .001$, $\eta^2 = .46$, and congruency were revealed, $F(1, 59) = 15.31$, $p < .001$, $\eta^2 = .21$. In addition, there was a significant interaction between error type and age group, $F(2, 59) = 8.96$, $p < .001$, $\eta^2 = .23$. To specify the effects of congruency on error type, an ANOVA with repeated measures was conducted for each group separately.

The results for 6-year-olds were similar to the two previous experiments: They made significantly more auditory errors than visual errors in the bimodal condition, suggesting an auditory dominance, $F(1, 17) = 14.13$, $p = .002$, $\eta^2 = .45$. Furthermore, they made significantly more errors in semantically congruent than in incongruent trials, $F(1, 17) = 6.86$, $p = .018$, $\eta^2 = .29$. No significant interaction between error type and congruency was revealed, $p = .10$.

In contrast to Experiment 1 and 2, 9-year-olds showed neither significant main effects nor an interaction, $p > .05$, suggesting a lack of sensory dominance.

Adults – in line with the previous experiments – made significantly more visual errors than auditory errors in the bimodal condition, suggesting visual dominance, $F(1, 19) = 4.53$, $p = .047$, $\eta^2 = .19$. Furthermore, they made significantly more errors in semantically congruent trials than in incongruent trials, $F(1, 19) = 5.66$, $p = .028$, $\eta^2 = .23$. There was no significant interaction between error type and congruency, $p = .45$. A response bias could again be ruled out.

Table 3

Mean error rates (in percentage) for the bimodal condition in total and separately for congruent and incongruent trials

	6-year-olds		9-year-olds		Adults	
Mean error rate in the bimodal condition	17.54	(8.3)	8.01	(5.6)	4.29	(2.7)
Auditory errors	10.94	(5.2)	4.17	(3.6)	1.48	(1.4)
Visual errors	6.60	(4.4)	3.84	(3.7)	2.81	(2.4)
Mean error rate in incongruent trials	14.93	(8.0)	6.77	(5.3)	2.97	(3.0)
Auditory errors	8.68	(4.7)	3.65	(3.9)	1.09	(1.5)
Visual errors	6.25	(4.7)	3.13	(3.8)	1.88	(2.9)
Mean error rate in congruent trials	20.14	(10.5)	9.24	(7.7)	5.63	(4.2)
Auditory errors	13.19	(7.6)	4.69	(4.9)	1.88	(1.9)
Visual errors	6.94	(5.5)	4.56	(5.5)	3.75	(4.1)

Note. Standard deviations in parentheses.

Discussion

For adults, the visual dominance effect was replicated in Experiment 3, which was again not affected by semantic congruency. In line with our predictions concerning the manipulation of color information, no visual dominance occurred in the group of 9-year-olds, neither in semantically congruent nor incongruent trials. Thus, the manipulation of salience by omitting color information seemed to restrain the privileged processing of visual stimuli in older children. In the group of the 6-year-olds, an auditory dominance effect was again revealed that was not affected by semantic congruency.

It could thus be concluded that the absence of color information does neither restrain the privileged processing of visual stimuli in adults nor of auditory stimuli in 6-year-olds, pointing to a quite robust dominance effect in these age groups, whereas the visual dominance of the 9-year-olds seems to be more vulnerable.

General Discussion

The two main questions of our study were: (1) whether visual dominance of 9-year-olds as well as auditory dominance of 6-year-olds (cf., Nava & Pavani, 2012) can be extended to the processing of complex and semantically meaningful stimuli, and (2) whether the manipulation of semantic congruency as well as of other stimulus characteristics (i.e., relative frequency and color information) affects the magnitude of sensory dominance effects in children and adults.

Sensory dominance effects in children and adults using complex stimuli. In all three experiments, a robust visual dominance effect was revealed for adults, whereas 6-year-olds exhibited an auditory dominance. Except for Experiment 3, a visual dominance effect could also be shown for 9-year-olds. This suggests that sensory dominance in children can be extended to the processing of complex and meaningful stimuli and does not only occur with simple lights and sounds, used in previous research (Nava & Pavani, 2012).

Experiment 2 suggested that increasing the frequency of bimodal relative to unimodal stimuli apparently reduced the mean error rate on bimodal trials but had no impact on the magnitude of the sensory dominance effects. As this was the fact for all age groups, one could assume a similar robustness of the sensory dominance effects regarding bimodal stimulus frequencies.

The manipulation of visual salience in Experiment 3 showed that the absence of color information did not affect the robust visual dominance in adults, and had no effect on auditory dominance in 6-year-olds, but seemed to undermine the visual dominance of 9-year-olds, who exhibited no sensory dominance in this particular experiment.

Obviously, there is a developmental trajectory of sensory dominance with an auditory dominance in early childhood and a visual dominance typically observed in adults with a transition occurring around the age of 9 years – which is underlined by our current study showing that sensory dominance is vulnerable to stimulus manipulation in this age group. Thus, the questions remain why this transition takes place around this age and what the underlying factors are.

One potential explanation refers to maturational processes of the brain. The subcortical auditory system matures earlier compared to the visual subcortical one (Lippé, Kovacevic, & McIntosh, 2009). Conversely, at the (higher-order) thalamocortical level, the tendency seems to be reversed. The visual thalamocortical system shows relative maturity at 5 months of age, whereas the maturation of the thalamic projections to the auditory cortex continues until 6 years of age. In addition, myelination begins earlier in the occipital lobe (visual processing center) than in the temporal lobe (auditory processing center). Synapse density shows a rapid increase in the occipital lobe until about 8 months of age that is followed by a decline, whereas the synaptic density of the auditory cortex increases until 4 years of age before connections are pruned (Lippé et al., 2009). In sum, the auditory system differentiates slower than the visual one. From this point of view, a weighted integration of visual and auditory inputs based on the maturational level of the two sensory systems in early childhood would rather benefit the visual one. Thus, one would expect a visual dominance in young children, rather than an auditory dominance.

Given that the auditory system is essential for language acquisition (Benasich, Thomas, Choudhury, & Leppänen, 2002) one might speculate that the dominance of the visual system could hamper language acquisition in a detrimental way. However, the attentional approach of Posner et al. (1976) might explain why this is not the case. As mentioned before, Posner and colleagues stated that humans actively attend to visual events as a means of compensating for the poor alerting properties of the visual signals. The active focus of attention, however, is mediated by higher order regions like the frontal cortex (Posner & Petersen, 1990), which is relatively immature during childhood (Anderson, 1998). Thus, an undermining of the auditory system due to the accelerated maturation of the visual system could be prevented, as the maturation of the visual system is a crucial but not sufficient condition for a visual dominance. Given that visual dominance is a byproduct of active attention towards visual stimuli, the maturation of the frontal cortex mediating these attentional processes is essential, too. Thus, whereas automatically attention-capturing auditory stimuli might favor auditory processing and therefore language acquisition in early childhood, the ongoing maturation of the frontal cortex in later childhood might favor the active focus of attention and thus the processing of visual stimuli. Given these premises, a dominance of the auditory system would be expected up to that age by which children have acquired fundamental language skills. At an early elementary school age, not only children’s auditory system has been matured, but they also have a vocabulary of about 5000 words, which they articulate almost error-free, they use and understand active and passive sentences, and can segment words into phonemes (for a summary, see Brandone, Salkind, Golinkoff, & Hirsh-Pasek, 2006). With the increasing differentiation of the frontal cortex, an "approximation" of the sensory systems could be carried out around nine years of age, giving way to a transition from a dominant auditory system towards an adult-like dominant visual system. As there are no sufficient explanations for developmental changes in sensory dominance yet, further research should address the underlying mechanisms. Potentially, cultural demands (e.g., the use of digital media in Western countries and rural-urban differences in access to and usage of digital media) rather than evolutionary perspectives (the persistence of auditory dominance up to 6 years of age due to language acquisition) should be taken into account.

Sensory dominance effects under the manipulation of semantic congruency and other stimulus characteristics. The second aim of our study was to investigate whether the manipulation of semantic congruency has an influence on the magnitude of sensory dominance effects. While sensory dominance in adults and 6-year-olds was not affected by semantic congruency, 9-year-olds were sensitive to this manipulation as visual dominance occurred under semantic congruency only. Thus, semantic congruency (besides spatiotemporal factors) seems to be a modulating factor in 9-year-olds. This is underpinned by the fact that the influence of congruency could be shown for two independent samples of 9-year-olds (Experiment 1 and Experiment 2).

The question remains why semantic congruency has an impact on sensory dominance in 9-year-olds but not in 6-year-olds or adults. One explanation could be the gradual change of sensory dominance. Whereas auditory dominance might have its peak around the age of 6 years and visual dominance is consolidated in adults, sensory dominance in 9-year-olds is yet in transition and maybe more prone to interference by stimulus characteristics. The fact that the absence of color information (Experiment 3) did not erase the visual dominance effect in adults but in 9-year-olds, underlines that visual dominance in this age group is more vulnerable. In line with that, the sensitivity for semantic congruency could reflect the same pattern. As all age groups exhibited significantly more errors in semantically congruent compared to incongruent trials, the crucial factor was supposed to be the presence of a semantic mismatch in incongruent trials providing participants with an extra cue. The manipulation of semantic congruency, however, did not influence the type of error, except for the group of 9-year-olds.

Six-year-olds exhibited significantly more auditory than visual errors and adults exhibited significantly more visual than auditory errors in bimodal trials, irrespectively of whether they were presented with semantically congruent or incongruent trials. Thus, in both conditions, a sensory dominance effect was revealed. In contrast, 9-year-olds made significantly more visual errors than auditory errors on semantically congruent trials, but no significant difference and therewith no sensory dominance was revealed on semantically incongruent trials. Thus, in all age groups, the presence of a semantic mismatch affected the mean total error rate (taken auditory and visual errors together), but only in the group of 9-year-olds, it had an impact on the type of error. As visual dominance was clearly overridden by the semantic mismatch on incongruent trials in this age group, one could assume that sensory dominance of 9-year-olds is more prone to interference.

However, regarding the null effect of semantic congruency on sensory dominance in 6-year-olds and adults, one should take the sample size into account. Thus, there might be an effect of semantic congruency on sensory dominance in 6-year-olds and adults, which is too small to be detected with the underlying sample size. On the contrary, also by increasing the test power by taking a greater number of participants into account no effects of semantic congruency on sensory dominance in adults were found in the study of Koppen et al. (2008, Experiment 2), suggesting our results are not due to the sample size at least for the group of the adults.

Concluding remarks. Our results first suggest that sensory dominance in children and adults is not restricted to simple stimuli such as lights and sounds, but can be extended to semantically meaningful stimuli. This implies a relative robustness of the sensory dominance effects first reported by Nava and Pavani (2012). Second, semantic (in-)congruency did not affect the magnitude of the auditory dominance effect in 6-year-olds and visual dominance effect in adults, but was a modulating factor of the visual dominance in 9-year-olds (Exp. 1 and 2). This is a novel finding, as it shows that the Colavita effect can be modulated by factors other than spatial and temporal congruency. Third, the absence of color information (Exp. 3) did not affect dominance effects in 6-year-olds and adults, while the visual dominance in 9-year-olds disappeared. This suggests that sensory dominance is more robust in 6-year-olds and adults than in 9-year-olds, implying a transitional stage around this age.

Future perspectives. A longitudinal investigation of sensory dominance would be more appropriate to identify the typical trajectory of multisensory interactions. Furthermore, to solve the question why multisensory interactions change in the course of development, one might investigate the neural substrates of the Colavita effect (in terms of the auditory stimulus not being perceived in the presence of a visual stimulus). Taking older children and adults into account, one could, for example, compare the pattern of brain activation in the auditory cortex when the auditory component of a bimodal stimulus is detected versus when it is not (i.e., when the Colavita visual dominance effect occurs).

From a clinical point of view, tracing how multisensory interactions typically develop may contribute to a better identification of deviating behavioral patterns and support the development of early diagnostic strategies (Nava & Pavani, 2012). For example, children with autism spectrum disorders (ASD) appear to have impairments in their sensory functioning (cf., Stevenson, Siemann, & Schneider et al., 2014). Further research examining the nature and extent of processing differences in autistic compared to non-autistic children, assessing their emergence early in development, and relating these findings to the core deficits in ASD would contribute to a broader understanding of this development disorder.

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Highlights

- We investigate sensory dominance in children and adults.
- Six-year-olds are dominated by audition, adults by vision in bimodal trials.
- Visual dominance is less robust in 9-year-olds.
- Semantic congruency and stimulus color affect visual dominance of 9-year-olds.
- There is a fundamental transition of sensory dominance around the age of 9 years.