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Highlights

- High visual attention load eliminates visual interference in children and adults.
- Even at high load, multimodal distractors influence adults and older children.
- Increased visual load 'shields' younger children from multimodal interference.
- Developmental research reveals mechanisms controlling attention in real life contexts.

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Multi-modal distraction: Insights from children's limited attention

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How does the multi-sensory nature of stimuli influence information processing? Cognitive systems with limited selective attention can elucidate these processes. Six-year-olds, 11-year-olds and 20-year-olds engaged in a visual search task that required them to detect a pre-defined coloured shape under conditions of low or high visual perceptual load. On each trial, a peripheral distractor that could be either compatible or incompatible with the current target colour was presented either visually, auditorily or audiovisually. Unlike unimodal distractors, audiovisual distractors elicited reliable compatibility effects across the two levels of load in adults and in the older children, but high visual load significantly reduced distraction for all children, especially the youngest participants. This study provides the first demonstration that multi-sensory distraction has powerful effects on selective attention: Adults and older children alike allocate attention to potentially relevant information across multiple senses. However, poorer attentional resources can, paradoxically, shield the youngest children from the deleterious effects of multi-sensory distraction. Furthermore, we highlight how developmental research can enrich the understanding of distinct mechanisms controlling adult selective attention in multi-sensory environments.

1. Introduction

The effectiveness of cognitive functioning in everyday life is determined by the ability to focus on a task while ignoring concurrent distracting stimuli (i.e., *selective attention*). Models of attentional selection were greatly advanced by "perceptual load theory" (e.g., Lavie, 1995,2005; Lavie & Tsal, 1994, 2011), proposing that the extent to which such irrelevant stimuli are distracting is determined by the degree to which the currently performed task exhausts one's available attentional resources. This influential proposal operationalized "distraction" as interference on one's primary task by task-irrelevant stimuli and we shall here follow this convention. The current study demonstrates that studying distraction in real-life environments, multi-sensory by nature, can reveal other mechanisms important for controlling attention, and that their importance might be more readily witnessed by studying cognitive systems whose attentional control is developing (e.g., children).

1.1. Attentional allocation in unimodal environments

Lavie and Tsal (1994) argued that attentional resources, in particular their limited nature, are what determines whether stimuli irrelevant to the current task will be processed. Lavie and colleagues provided evidence for this claim in a series of now classical studies that employed the response-competition task (Lavie, 1995; Lavie & Cox, 1997; Lavie & Tsal, 1994): Typically, when one is searching

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for one of two target letters (X or N) amongst a small number of letters (a task posing low perceptual load demands), concurrently presented peripheral distractors trigger reliable stimulus–response compatibility effects, i.e., slower search times on trials in which these peripheral stimuli prime a response opposite to the target response (e.g., an X when the target was an N). However, during search amongst a larger number of similar letters (a task posing higher perceptual load demands) compatibility effects are strongly reduced. In line with perceptual load theory (Lavie, 1995), in a task posing low perceptual demands, remaining attentional resources are automatically allocated to task-irrelevant stimuli in the environment. This results in distraction, as both target and distractors are processed up to the stage of their semantic representation and associated motor response. Such a situation contrasts with processing of distractors in a task that is perceptually demanding: Their processing is reduced or even eliminated, because the task is thought to be exhausting the available attentional resources.

1.2. Attentional allocation when faced with cross-modal distraction

While the importance of the nature of one's primary task in constraining distraction has since been replicated with various methods, measures and populations (see Lavie, 2010, for a review), of particular value is testing whether predictions of perceptual load theory hold against everyday situations, such as in the context of cross-modal distraction. Early seminal work by Allport and colleagues (e.g., Allport, Antonis, & Reynolds, 1972) had demonstrated that a fairly complex auditory task (i.e., auditory shadowing) can be performed alongside a demanding visual task (i.e., sight-reading music), which suggests a limited effect of processing load across senses. Further contrasting evidence was provided by Tellinghuisen and Nowak (2003), who used a version of the response-competition task adapted to a cross-modal context: when peripheral letter distractors are presented auditorily during search for visual letter targets, they, unlike visual distractors, filter into further processing stages, causing interference under conditions of high visual perceptual load.

The residual interference effects from auditory distractors on visual tasks have been presented as evidence for separate attentional resources in vision and audition: Visual distractors do not impact attention on the primary task, presumably because attentional resources in the primary modality have been depleted, whereas separate resources are devoted to auditory distractors (Duncan, Martens, & Ward, 1997; Welch & Warren, 1980). However, recent studies have provided mixed evidence for this account (Jacoby, Hall, & Mattingley, 2012; Klemen, Büchel, & Rose, 2009; Parks, Hilimire, & Corballis, 2011). For example, high visual perceptual load was recently shown to induce inattentional deafness: Macdonald and Lavie (2011, Experiment 3) instructed participants to judge which of two coloured arms of a centrally presented cross was longer, while on some trials a task-irrelevant pure tone was presented. On trials where the two arms differed in length only slightly (a perceptually demanding task), conscious awareness of the tone was reduced compared to trials in which the difference in arm length was larger (a task with lower perceptual demands). In contrast to separate-resources models, these results indicate that in adults, even in cross-modal contexts, at least under some conditions (e.g., very high visual load and/or complete task irrelevance of the auditory distractor) attentional resources are shared across modalities.

1.3. Attentional allocation in multi-sensory environments

The jury is therefore still out on whether cross-modal distraction can be entirely removed by increases in visual attentional load and on what drives cross-modal distraction, i.e., interference, on a visual task. Particularly informative to this debate are studies employing stimuli that present redundant information to more than one modality at once (e.g., Matusz & Eimer, 2011, 2013; Van der Burg, Talsma, Olivers, Hickey, & Theeuwes, 2011). Multiple sources of congruent information are integrated into a unified multi-sensory percept that triggers enhanced behavioural and/or neural responses, both when the information is redundant at a low perceptual (e.g., temporal and/or spatial alignment; e.g., Santangelo & Spence, 2007, but see Spence, 2010) or high semantic level (e.g., Laurienti, Kraft, Maldjian, Burdette, & Wallace, 2004; for a review, see Alais, Newell, & Mamassian, 2010). However, this body of research has tended not to use the classical visual perceptual load paradigms. Yet, this novel extension is much needed, as it would bridge the perceptual load theory of selective attention and theories of multi-sensory processing, which traditionally have been developed separately. Do increased perceptual demands of the primary task reduce distraction elicited by multi-sensory events? If audiovisual distractors were processed under both lower and higher visual load, this would provide further support for the idea that, at least under some conditions, separate attentional resources are deployed (Tellinghuisen & Nowak, 2003). Interestingly, multi-sensory distractors should generally result in more robust distraction (i.e., interference on the primary task) than unimodal distractors because at each level of visual perceptual load they would engage attentional resources in two modalities. If such effects were indeed observed, this would call for a revision of the perceptual load theory to accommodate multi-sensory distraction.

1.4. Insights from developmentally-informed research

Some of the strongest evidence for the critical role of attentional resources in reducing distractor processing has been provided by research involving young children, whose attention is known to be less efficient than that of adults (e.g., Plude, Enns, & Brodeur, 1994; Trick & Enns, 1998). In a version of the response-competition task, Huang-Pollock, Carr, and Nigg (2002) found that children as young as seven years of age were more distracted by peripherally-presented letters than young adults when the search task was easy, consistent with poorer mechanisms of distractor interference control in children (Posner, Rothbart, & Thomas-Thrapp, 1997). Under conditions of high perceptual load, children were not differentially influenced by distractors, like adults, as indexed by a lack of distractor compatibility effects on RTs (see also Maylor & Lavie, 1998, for similar implications from data from elderly participants). This pattern of results suggested that children are less able than adults to control stimulus–response conflict (a marker of poor attentional control), but only until attentional-capacity limits are reached.

A developmental approach might be beneficial also in assessing whether the predictions of perceptual load theory extend to how attentional resources are allocated to distractors presented in multiple sensory modalities. Do increased perceptual demands of the primary task reduce distraction elicited by multi-sensory distractors in children, who have fewer attentional resources, as well as in adults? A developmentally-informed design therefore has the potential to provide insights into distinctive mechanisms controlling attention in multi-sensory contexts. Critically, while children and adults seem to be similarly 'shielded' from visual distraction at higher levels of visual load, this might not hold true for distractors in other modalities, and especially ones presenting information to multiple sensory modalities at once. In systems possessing weak attentional resources, the perceptual load theory in its current form would expect higher levels of visual load to exhaust these resources earlier, thus decreasing the processing of multi-sensory distractors compared to the fully developed system. However, if interference from multi-sensory distractors was found for children, this would call for a revision of perceptual load theory to accommodate the role of multi-sensory distraction. One would need to account for how increases in the perceptual load of the primary task may shield from distraction under some conditions but not others. These are as yet untested hypotheses, despite their clear importance for selective attention models and for the understanding of attentional control development.

1.5. The current study: approach and predictions

The aim of this study was to investigate developmental differences in how the perceptual load of a primary visual selective attention task constrains the processing of multi-sensory, i.e., audiovisual, distractors. For this purpose, we employed a traditional perceptual load paradigm, with a novel modification: For the first time, peripheral distractor stimuli were not only presented visually or auditorily, but also audiovisually. Secondly, and again for the first time, age-related differences in attentional abilities were used to probe the limits of multi-sensory distraction. Six-, 11- and 20-year-olds searched for a visual coloured shape (red square or green circle) in arrays consisting of 1 (a lower visual load condition) or 4 (a higher visual load condition) coloured shapes. For visual distractors, at the lower level of visual load we predicted larger compatibility effects for children than adults, because of children's poorer control of stimulus–response conflict, an attentional control mechanism (replicating Huang-Pollock et al., 2002). At the higher level of load, the exhaustion of visual attentional resources should eliminate visually-induced compatibility effects across all age groups. For auditory distractors, compatibility effects in adults were expected not to be modulated by visual load (Tellinghuisen & Nowak, 2003), although these findings remain controversial (Macdonald & Lavie, 2011). Critically, in adults we expected robust distraction in response to audiovisual distractors, i.e., compatibility effects at levels of lower and higher load that, at a minimum, resemble the processing of the most effective distractor at each level. A developmentally-inspired design provided informative differential predictions with respect to distinct mechanisms controlling distraction in multi-sensory contexts: if attentional resources are joint across modalities (Macdonald & Lavie, 2011), auditorily – and audiovisually-induced compatibility effects should be eliminated or at least strongly reduced across all age-groups at the higher level of visual load. If instead separate attentional resources exist for the visual and auditory modality, audiovisually-induced compatibility effects should not be reduced by visual load, even in the youngest children.

2. Method

2.1. Participants

Thirty "6-year olds" (mean age 6.7 years, age range 6–7.2 years) and thirty-three "11 year olds" (mean age 10.9 years, age range 9.9 years–11.8 years), as well as thirty adults (undergraduates students, mean age 20 years, age range 18.1–22.4 years) took part. All adult participants provided informed consent and parental consent was also obtained for each child, according to the procedures set out by the appropriate Ethics Review board. Children were rewarded for participation with a certificate and stickers, whereas adults participated without compensation. All had normal hearing and normal or corrected-to-normal vision.

2.2. Stimuli, procedure and design

Stimuli were presented using E-prime v.2 on a screen located approximately 50 cm from the participants. Each trial began with an 800-ms-long central fixation point, immediately followed by a 200-ms-long search display. As shown in Fig. 1, participants searched for coloured shapes with a particular conjunction of features, i.e., either a red square or a green circle, and pressed an appropriate, clearly labelled keyboard button upon detection. In set-size 4 blocks, the target ($0.6^\circ \times 0.6^\circ$) was surrounded by three nontarget shapes drawn randomly from a set of red and green triangles, circles and squares ($0.6^\circ \times 0.6^\circ$), appearing randomly and equiprobably in one of six possible locations along the circumference of a circle centred at fixation (2.1° radius). In set-size 1 blocks, the target was presented alone at one of the six locations.

The visual peripheral distractor was a larger ($0.8^\circ \times 0.8^\circ$) red or green square or circle shape presented at a distance of 4.1° from the fixation point. The auditory distractors were voice recordings of the words 'red' or 'green' presented laterally (both lasting 500 ms, see Supplementary Materials available online for a parallel

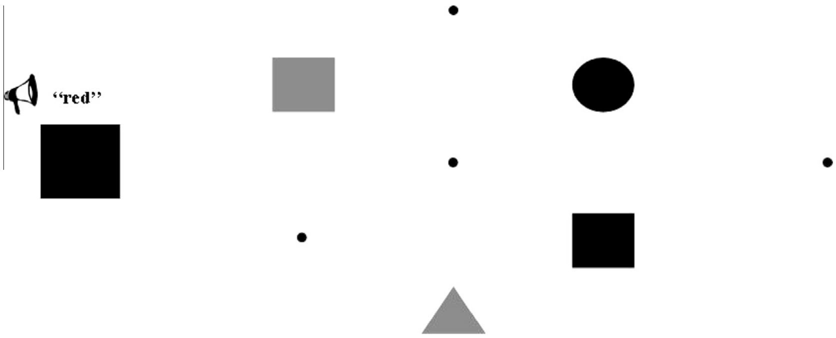


Fig. 1. An example of a search display, in which a red-square (in black) target was presented at set-size 4 concurrently with a target-compatible audiovisual peripheral distractor.

study presenting auditory stimuli for 200 ms). In the audiovisual distractor condition, the distractor was presented visually to either left or right of fixation and concurrently to either the left or right speaker. The experiment lasted 30 min, deemed a length appropriate for the youngest children following a pilot study. Ten blocks of 24 trials were presented, five blocks for each of two set-size conditions. For each of the two target identities, each of the three distractor types was presented four time (two trials for each of two compatible and incompatible conditions), thus resulting in 24 trials in each block. The experiment consisted of 10 blocks (five blocks for each of two set-size conditions), with a total of 240 experimental trials.

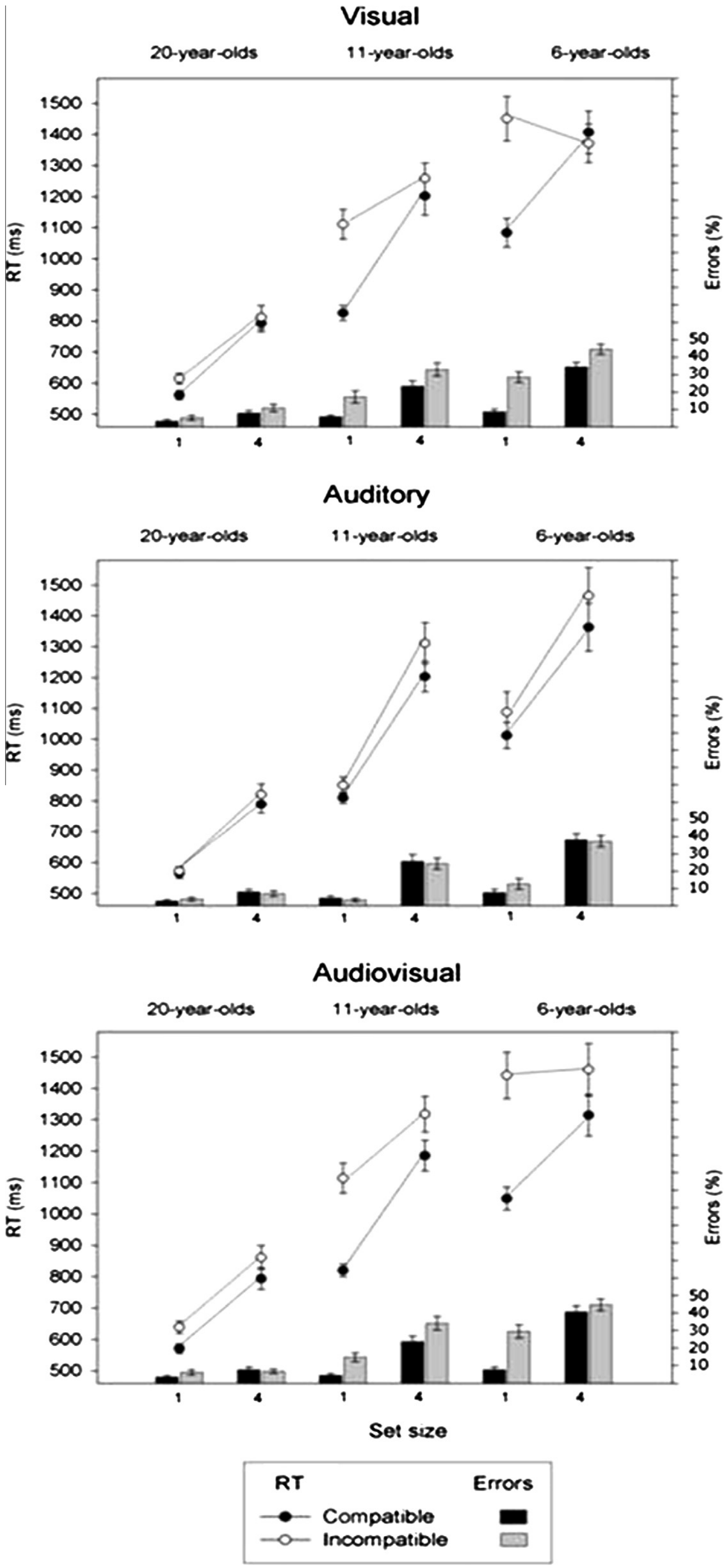
3. Results

Means of median correct reaction time (RT) and error rates are reported in Fig. 2. A four-way mixed analysis of variance (ANOVA) was conducted on the RTs data, with compatibility (distractor compatible versus incompatible with the target identity), set-size (1 versus 4 coloured shapes in the search array), and distractor type (visual versus auditory versus audiovisual) as within-subjects factors, and age (adults versus 11-year-olds versus 6-year-olds) as a between-subjects factor. RTs were modulated by age, $F(2,90) = 59.51$, $p < .001$, $\eta_p^2 = .57$, with gradually faster responses across age-groups (1265 ms versus 1070 ms versus 699 ms), all p's < .001. There were main effects of compatibility, $F(1,90) = 120.47$, $p < .001$, $\eta_p^2 = .57$; distractor type, $F(1.83,164.92) = 16.1$, $p < .001$, $\eta_p^2 = .15$; and set-size, $F(1,90) = 111.3$, $p < .001$, $\eta_p^2 = .55$. Compatibility and set-size interacted, $F(1,90) = 24.41$, $p < .001$, $\eta_p^2 = .21$, and age modulated this interaction, $F(2,90) = 7.48$, $p < .001$, $\eta_p^2 = .14$, suggesting that increasing set-size reduced distraction, but also that this effect differed across age groups. A three-way interaction between compatibility, set-size and distractor type, $F(2,180) = 21.8$, $p < .001$, $\eta_p^2 = .2$, indicated that the effect of increased set-size on distraction also differed depending on the type of distractor.

Critically, a four-way interaction between compatibility, set-size, distractor type and age was observed, $F(4,180) = 3.89$, $p < .01$, $\eta_p^2 = .01$. To investigate the sources of this interaction, compatibility effects were analysed separately for each distractor type. To summarize these results, while increased visual set-size removed interference effects of visual-only distractors in all age-groups, audio-visual distractors affected adults at both levels of set-size. For all children, increased visual set-size reduced audiovisual distraction significantly, and to the level of only a trend for the youngest children. In addition, we investigated the 4-way interaction effect by comparing the effects of distractor types directly: At set-size 1, for all groups, audio-visual and visual distractors resulted in larger interference effects compared to auditory distractors. At set-size 4, adults' responses only were more affected by audio-visual than by auditory distractors.

3.1. Visual distractors

Overall faster responses on compatible relative to incompatible trials (965 ms versus 1084 ms), $F(1,90) = 53.44$, $p < .001$, $\eta_p^2 = .37$, were modulated by set-size, $F(1,90) = 35.45$, $p < .001$, $\eta_p^2 = .28$. Pair-wise comparisons revealed reliable compatibility effects elicited at set-size 1 (228 ms, $p < .001$), but not set-size 4 (14 ms, $p = .56$). Importantly, compatibility effects were modulated by age, $F(2,90) = 6.62$, $p < .001$, $\eta_p^2 = .13$. Here and henceforth, significant interactions were investigated with analyses of simple main effects. Pair-wise comparisons revealed that overall compatibility effects triggered by visual distractors in both younger (149 ms) and older (173 ms) children were reliably larger when compared to adults (36 ms), smaller $p < .05$, but no difference was found between the two groups of children, $p = 1$. As predicted, there was a three-way compatibility × set-size × age interaction, $F(2,90) = 8.07$, $p < .001$, $\eta_p^2 = .15$, indicating that reductions of compatibility effects across set-sizes differed in adults and children (see Fig. 2, top panel). Pair-wise comparisons demonstrated that in all age groups reliable compatibility effects were elicited at set-size 1 (345 ms in 6-year-olds; 281 ms in 11-year-olds, and 53 ms in adults, all p's < .001). Separate pair-wise comparisons demonstrated these compatibility effects elicited at set-size 1 were reliably larger in both younger and older children compared to adults, p's < .001, but not different across the two groups of children, $p = .83$. Critically, at set-size 4 visually-induced compatibility effects were completely eliminated in all age groups (smallest $p = .076$). To



Q11 **Fig. 2.** Median correct RTs and mean error rates observed for young adults (left panels), 11-year olds (middle panels) and 6-year olds (right panels) on compatible and incompatible trials at two levels of set size, shown separately for visual, cross-modal and audiovisual distractors. The error bars represent standard error of the mean.

investigate whether the observed pattern was due to generally slower responses in children, compatibility effects were scaled by average RTs across conditions (see Huang-Pollock et al., 2002; Maylor & Lavie, 1998). An ANOVA on these proportional scores retained a set-size x age group interaction, $F(2,90) = 3.57$, $p < .05$, $\eta_p^2 = .07$. As seen previously, for all groups significant compatibility effects (p's < .001) at set-size 1 were eliminated at set-size 4 (p's > .11), p's < .05.

3.2. Auditory distractors

RTs were overall reliably faster on compatible versus incompatible trials (946 ms versus 1005 ms), as indexed by a main effect of compatibility, $F(1,90) = 11.42$, $p < .001$, $\eta_p^2 = .12$. As shown by Fig. 2 (middle panel), in contrast with the effects found for visual distractors, these compatibility effects were not modulated by age, $F(2,90) = 1.45$, $p = .24$, set-size, $F(1,90) = 1.78$, $p = .19$, or an interaction between set-size and age, $F < 1$. An anonymous reviewer helpfully pointed out that, although interaction effects did not reach statistical significance, visual inspection of Fig. 2 suggested that compatibility effects might not have been reliably triggered in adults by auditory distractors (see left column in the middle panel). Separate pair-wise comparisons confirmed this for set-size 1 (7 ms, $p = .15$), with distraction effects observed at set-size 4 (30 ms, $p < .05$). In 11-year-olds compatibility effects were reliably present both at set-size 1 (42 ms, $p < .05$) and set-size 4 (94 ms, $p < .05$), while in 6-year-olds they were significant at set-size 1 (79 ms, $p < .05$), but at a level of a non-significant trend at set-size 4 (103 ms, $p = .06$). To reiterate, the most conservative statistical analyses revealed no differences across these compatibility effects. Both this and the lack of reliable cross-modal distraction effects at lower levels of load in adults are consistent with previous work (Tellinghuisen & Nowak, 2003).

3.3. Audiovisual distractors

There were overall faster responses on compatible relative to incompatible trials (948 ms versus 1124 ms), $F(1,90) = 98.69$, $p < .001$, $\eta_p^2 = .52$. This effect was modulated by set-size, $F(1,90) = 19.95$, $p < .001$, $\eta_p^2 = .18$, with compatibility effects larger at set-size 1 than set-size 4 (243 ms versus 107 ms). Importantly, compatibility interacted with age, $F(2,90) = 9.22$, $p < .001$, $\eta_p^2 = .17$, with larger compatibility effects when both younger (242 ms) and older (211 ms) children were compared to adults (68 ms), smaller $p < .01$, but with no difference between two groups of children, $p = 1$. Similarly to visual distractors, a three-way compatibility × set-size × age interaction was found, $F(2,90) = 5.87$, $p < .01$, $\eta_p^2 = .12$, suggesting that the reduction of compatibility effects as a function of set-size differed again across ages (see Fig. 2, bottom panel). In an analysis of simple main effects, a first series of separate pair-wise comparisons revealed that the three-way interaction effect was driven by the fact that compatibility effects emerged at both levels of set-size for adults (68 ms and 68 ms, both $p < .001$), and for 11-year-olds (285 ms at set-size 1, while they were reduced at set-size 4, 136 ms, smaller $p < .01$), whereas for 6-year-olds they were reliable at set-size 1 (371 ms, $p < .001$), but not at set-size 4 (113 ms, $p = .054$). A further series of pair-wise comparisons carried out on these compatibility effects revealed that compatibility effects were reliably reduced between set-size 1 and 4 for both younger ($t(29) = 3.41$, $p < .01$) and older children ($t(32) = 3.04$, $p < .01$) , but not adults ($t(29) = .01$, $p = .99$). An ANOVA run on proportional compatibility effects (i.e., compatibility effects scaled by average RTs across conditions as above) for audiovisual distractors was carried out to compare them more fairly across age-groups, as these differed widely in average RT. The ANOVA retained a set-size × age group interaction, $F(2,90) = 4$, $p < .05$, $\eta_p^2 = .09$. For all age groups audiovisual distraction effects were reliably present at set-size 1 (scaled compatibility effects were .271, .274, .109 for younger, older children and adults respectively, p's < .001), while at set-size 4 they were eliminated for 6-year-olds (.070, $p = .078$), $p < .01$ for the decrease from set-size 1 to set-size 4, and attenuated for 11-year-olds (.109, $p < .01$), $p < .001$ for the decrease from set-size 1, but remained robust across this set-size for adults (.080, $p < .001$), $p = .15$ for the null decrease from set-size 1.

3.4. Differences across distractor types

The interaction effects between distractor type and the other factors, reported above, called for an additional explicit comparison of distractor effects. We ran three separate repeated measures three-way ANOVAs, one for each age group of interest, with compatibility, set-size, and distractor type as within-subjects factors. For younger children, the interaction between distractor type, set-size and compatibility was significant, $F(2,58) = 11.425$, $p < .001$, $\eta_p^2 = .283$, driven by simple main effects of distractor type for set-size 1, for both compatible, $F(2,28) = 5.228$, $p = .011$, $\eta_p^2 = .274$, and incompatible trials, $F(2,28) = 19.199$, $p < .001$, $\eta_p^2 = .578$, but not for set-size 4 ($p > .305$). At set-size 1, younger children responded significantly faster with auditory distractors than with visual and audiovisual distractors, for compatible and incompatible trials ($p < .013$ and $p < .001$, respectively), whereas visual and audiovisual distractors did not differ ($p = .159$). For older children, there was a reliable interaction between distractor type, set-size and compatibility, $F(2,58) = 8.959$, $p < .001$, $\eta_p^2 = .219$, driven by a simple main effect of distractor type for incompatible trials at set-size 1, $F(2,28) = 31.015$, $p < .001$, $\eta_p^2 = .667$. Older children were faster at responding with incompatible auditory than incompatible visual and audiovisual distractors ($p < .001$), whereas visual and audiovisual distractors did not differ ($p > .922$), and there were no distractor effects on compatible trials ($p = .880$). For adults, there was only a two-way interaction between distractor type and compatibility, $F(2,58) = 8.177$, $p = .001$, $\eta_p^2 = .220$, driven by a simple main effect of distractor type for incompatible trials, $F(2,28) = 14.865$, $p < .001$, $\eta_p^2 = .515$, but not compatible trials ($p = .920$). Adults were faster with incompatible auditory distractors ($M = 695.45$ ms) than with visual distractors (713.55 ms, $p = .035$) and were slowest with audiovisual distractors (747.8 ms, $p = .001$ compared to both auditory and audiovisual distractors). As this pattern may suggest evidence of enhanced multi-sensory compared to unimodal effects in adults, targeted pairwise comparisons on compatibility effects at each level of set-size were conducted. At set-size 1, for adults compatibility effects for audiovisual (68 ms) and visual distractors (i.e., the most effective unimodal distractor at that set-size, 53 ms) did not differ significantly, $p = .310$. At set-size 4, for adults the compatibility effect for audiovisual distractors (68 ms) was significantly larger than that for auditory distractors (i.e., the most effective unimodal distractor at that set-size, 30 ms, $p = .024$).

3.5. Accuracy data

Error rates data failed to fulfil the parametric test assumptions. Wilcoxon's signed rank tests showed visually-induced compatibility effects at set-size 1 and 4 for both 6-year-olds (20% and 10.3%, p's < .001) and 11-year-olds (11.4% and 9.1%, p's < .05), but not in 20-year-olds (1.8%, $p = .13$, and 3.1%, $p = .053$). Auditorily-induced effects were reliable only in 6-year-olds at set-size 1 (5.1%, $p < .05$), p's > .27 for other groups and conditions. Audiovisually-induced effects were significant for 11-year-olds at set-size 1 and 4 (11.2% and 10.6%, p's < .001), and significant at set-size 1 but not 4 for 6-year-olds (21.8%, $p < .001$, and 3.8%, $p = .5$) and 20-year-olds (2.7%, $p < .03$ and −.09%, $p = .68$), respectively. Despite the fact that the error rates were particularly high for some of the youngest children (see Fig. 2), the reduction in compatibility effects as measured by RTs with increased set-size was not due to a speed accuracy trade-off. The same pattern of results was revealed by an identical four-way ANOVA when participants with error rates above 33% (twelve 6-year-olds and two 11-year-olds) were excluded from the analyses, and thus these analyses are not reported here.

4. Discussion

The main aim of the present study was to investigate whether poorer attentional selection 'shields' from interference from distractors that present information in multiple modalities. For this purpose, 6-, 11- and 20-year-olds searched for coloured-shape targets under variable visual perceptual load demands while ignoring visual, auditory and audiovisual distractors appearing in the periphery. The key overall finding was that whether increases in visual perceptual load decreased distraction depended critically on the nature of the distractor and on the age of the observer. We evaluate the novelty of these results, from their contributions to the understanding of visual selective attention development, its extension to multi-sensory environments and relationships with the broader literature on attentional control.

4.1. Developing attentional allocation in unimodal environments

The pattern of compatibility effects triggered by visual distractors is consistent with the findings of Huang-Pollock et al. (2002). Under low visual attention demands, both younger groups were more distracted by peripheral shapes than adults, as indexed by larger compatibility effects. These findings replicated how, under low visual attentional demands, visual distractors are more disruptive for developing systems because of poorer abilities to control conflict at the level of response selection. Indeed, the low load condition presented observers with a single central stimulus and a peripheral flanking distractor. Higher visual load eliminated distractor effects at all ages, a finding previously interpreted as suggesting that visual attentional demands lead to adult-like levels of distraction by exhausting attentional resources, and therefore diminishing the size of a visuo-spatial attentional window (*earlier selection*, Huang-Pollock et al., 2002). Playing the devil's advocate, although it is clear that larger visual interference effects at low visual load in children compared to adults are entirely eliminated with high visual load, it is hard to verify whether children's visual attentional resources asymptote significantly earlier compared to adults with the current setup. This is because we used two levels of load (the minimum but commonly used number of levels in perceptual load experiments), rather than three or four levels. However, Huang-Pollock et al. (2002) demonstrated that in children (visual) distraction is eliminated at a load level of four items, while six are required for adults, suggesting that children's resources do indeed asymptote earlier. Here we chose to pit against each other two levels of load because we aimed to focus instead on our *multi-sensory* questions in a developmental context: The youngest children would not have been able to complete an experiment involving multiple distractor types across many visual-load levels. Yet, the youngest participants were vital in testing whether the effects of multi-sensory information on distraction under higher visual load depend very simply on the depletion of a pool of central attentional resources, regardless of the modality of the distractor.

4.2. Developing attentional allocation in multi-sensory environments

Our most novel findings centre on the compatibility effects triggered by multi-sensory (i.e., audiovisual) distractors. In adults, audiovisually-induced effects were reliably present at both lower and higher level of visual perceptual load, and not modulated by it. In turn, this suggests that in fully developed cognitive systems attention is allocated to the processing of information across modalities independently of the level of perceptual load imposed by a primary selective attention task. These results cannot be easily reconciled with the existing versions of accounts postulating that a single attentional resource is allocated separately across the senses. If limited-capacity attentional resources were jointly allocated to stimuli in multi-sensory environments, multi-sensory distraction should have been reduced with increased visual load. Notably, the robust multi-sensory distraction effects were not due to insufficiently high visual load: In our Follow-up Study, we replicated multi-sensory distraction effects of similar size across four levels of visual load in adults (see Fig. S1).

Remarkably, multi-sensory distraction effects were not consistently enhanced compared to the effects triggered by the most effective unimodal distractor at a given load level, even for adults. The enhancement of effects triggered by multi- versus unimodal stimuli is regarded as a hallmark of multi-sensory integration, as fusion of information across the senses facilitates its processing by enabling the brain to extract any redundancies (perceptual and/or semantic; e.g., Laurienti et al., 2004; Matusz & Eimer, 2011). The current study did not set out to test the presence or absence of multi-sensory integration per se. However, the multi-sensory effects broadly *resembled* the distraction effects triggered by the most effective unimodal distractors. This may be because multi-sensory integration is maximal when to-be-integrated stimuli are presented synchronously (Stevenson & Wallace, 2013, for a review) and in the absence of other competing stimuli (e.g., Sanabria, Soto-Faraco, Chan, & Spence, 2005). These findings are important in their own vein by demonstrating that (in fully developed cognitive systems) multi-sensory distractors are associated with robust processing even when the presence of multiple stimuli in either sensory modality might reduce the chance of multi-sensory integration and its benefits. But what could these effects depend upon, if not full multi-sensory integration? We believe that the mechanisms responsible for these multi-sensory effects were further elucidated by the results from individuals whose selective attention abilities are only developing.

In contrast with adults, for both groups of children, higher visual load decreased multi-sensory distraction, and, for the youngest children alone it reduced it very severely to a trend. In older children and adults, multi-sensory distractors continued to trigger reliable distraction under high perceptual task demands, in contrast with its elimination with visual-only distractors. This pattern is hard to reconcile with the current version of the perceptual load theory, as limited-capacity attentional resources jointly allocated to distractors should have been exhausted at higher levels of load for all participants, and particularly for both groups of children, given their lower visual attentional resources (Huang-Pollock et al., 2002).

4.3. Developing attentional allocation in multi-sensory environments: proposed mechanisms

The seemingly puzzling pattern of multi-sensory distraction effects observed across the different age groups is consistent with the dynamic interplay between distinct non-mutually exclusive top-down attentional control mechanisms that follow different developmental trajectories. First, at the lowest levels of load, both groups of children were strongly and equally distracted by multi-sensory stimuli. We agree with Huang-Pollock et al. (2002) that, in contexts posing low perceptual demands, the prolonged development of *response-selection control or late selection* will shape how individuals from different age groups will be distracted, and we showed for the first time that this applies to uni- and multi-sensory contexts alike.

Critically, however, with our novel developmentally-inspired multi-sensory setup we were also able to demonstrate additional top-down attentional control mechanisms at play. Searching for visual targets whose semantic attributes (i.e., identity) can be represented in both the visual and the auditory modality, as is the case in this adaptation of the perceptual load paradigm, is likely to facilitate the processing of all stimuli, within the same and/or another sensory modality, that share the semantic features with the sought target. In support of this second *non-spatial high-level and goal-driven bias*, eye-tracking studies have demonstrated that children as young as six can use semantic information to guide their attention (Fletcher-Watson, Collis, Findlay, & Leekam, 2009). This would explain why both older children and adults alike showed multi-sensory distraction across lower and higher levels of load, although this effect was reduced by visual load in the older children. Why was audio-visual distraction so severely reduced by load in the younger children? It is likely that a third distinct attentional mechanism was at play here: Increases in perceptual task demands can attenuate attentional selection of multi-sensory stimuli (e.g., Van der Burg, Olivers, & Theeuwes, 2012) by motivating observers to focus on the likely spatial location of the target (i.e., the *top-down narrowing of spatial attentional window or early selection*), especially in the absence of a well-established non-spatial top-down bias for relevant information in any modality. Indeed, spatial attentional biases, unlike the more complex goal-based biases above, have been frequently demonstrated in very young children (for a review, see Scerif, 2010). A mechanism whereby increasing task demands triggers the focusing of attention around the likely target location might develop earlier than the other, non-spatial top-down control mechanism, thus paradoxically 'shielding' younger children from distraction.

4.4. The findings in context: relationships with the broader attentional control literature

At first blush, the current findings contrast with the body of research proposing that young infants are born with a superabundance of cross-modal connections between early sensory cortices (Spector & Maurer, 2009), and that their attention is automatically guided towards intersensory redundancies (Bahrick, Lickliter, & Flom, 2004; Lickliter & Bahrick, 2013). Indeed, multiple articles cast doubt on whether young children truly show multi-sensory enhancement (e.g., Barutchu, Crewther, & Crewther, 2009; Gori, Del Viva, Sandini, & Burr, 2008; Nava & Pavani, 2013). Of note, those studies do not investigate multi-sensory attentional deployment, but rather multi-sensory redundancy, and therefore they highlight further the novelty of our study. For example, Nava and Pavani (2013) show interesting age-related differences in auditory processing, but again test this under conditions of low attentional demands, and when the auditory information is not task relevant. Here, we argue that the larger distraction effects in children than in adults found here under lower perceptual load demands for multi-sensory and visual distractors alike indicate that greater sensitivity to intersensory redundancy early in life might simply be limited to contexts where multi-sensory stimuli are presented alone. This further adds support to our argument that, in developing cognitive systems, attentional processing of multi-sensory stimuli is much more flexible and context-dependent than the current literature suggests.

Furthermore, the current findings provide insights that extend beyond the debate on visual selective attention and perceptual load. The broader literature on cognitive control also suggests strong cross-modal effects of auditory distraction on control processes in adults, both for Stroop-like interference effects (Roelofs, 2005) and visual search (e.g., Klapetek, Ngo, & Spence, 2012). Moreover, the counter-intuitive greater interference of multi-sensory distractors in efficient observers, compared to the paradoxical "protective" effect of poor attentional resources against distraction in children, converge with parallel findings on adults' privileged processing of (auditory) linguistic input on visual tasks even when this information is potentially detrimental (e.g., Huettig & Altmann, 2011; Salverda & Altmann, 2011). They also echo findings on the tantalising mix of bilingual advantages in executive control (e.g., Bialystok & Barac, 2012; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009) and disadvantages in aspects of language production (e.g., Runnqvist, Gollan, Costa, & Ferreira, 2013). It would be of great value, for example, to investigate how these distinct attentional and non-attentional mechanisms relate to each other, over "typical" monolingual development, in adult bilinguals and as bilingualism is established. Better attentional control seen in bilinguals may actually make them more susceptible to distractors due to their greater resources. For example, it is possible that in the context of high stimulus–response control and good monitoring abilities (e.g., Costa et al., 2009) bilinguals suffer greater interference for low-frequency semantic and syntactic representations (e.g., Runnqvist et al., 2013). Monolinguals may instead be shielded from this interference. Further interactions across these seemingly disparate literatures could be as productive as we believe is the case for perceptual load and multi-sensory attention.

In conclusion, we provided novel evidence that increasing the perceptual demands of the primary task might effectively shield systems of reduced attentional capacity from multi-sensory distractor interference. To reiterate, the present findings therefore highlight the importance of assessing individuals with different attentional capacity for better understanding of selective attention in real-life environments: Testing only adults would have erroneously suggested that increasing attentional demands in the visual modality plays no role in modulating distractor interference in multi-sensory contexts. In contrast, our developmentally-inspired design offered a tool to disentangle distinct mechanisms controlling attentional selection in complex environments. First, we demonstrated changes in stimulus–response interference control in unimodal and multi-sensory contexts, with significant differences between young and older children, and in turn adults, when tested under low perceptual load demands; second, we showed a change in attentional processing capacity, leading both younger and older children to align with adults at high load, but for visual distractors only; and, finally, we provided novel evidence for changes in the allocation of attention to task-relevant multi-sensory information, with vital differences in multi-sensory distraction under high visual load across all age-groups. Thus, the current findings support the predictions of perceptual load theory (Lavie, 1995, 2011), but call for its revision, so that it accommodates the multi-sensory nature of distractors and their variable task-relevance in real-life environments. Finally, they call for the need to test further key predictions of this theory against individuals with variable attentional abilities, as a way of informing mechanisms of efficient adult attentional control.

5. Uncited reference

Eimer, Van Velzen, and Driver (2002).

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2014.11.031.

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