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Children's perception of visual and auditory ambiguity and its link to executive functions and creativity

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Abstract

The phenomenon of perceptual bistability provides insights into aspects of perceptual processing not normally accessible to everyday experience. However, most experiments have been conducted in adults and it is not clear to what extent key aspects of perceptual switching change through development. The current research examined the ability of 6-, 8-, and 10-year olds (N = 66) to switch between competing percepts of ambiguous visual and auditory stimuli, and links between switching rate, executive functions and creativity. The number of switches participants reported in two visual (ambiguous figure, ambiguous structure-from-motion) and two auditory (verbal transformation, auditory streaming) tasks were measured in three 60-second blocks. Additionally, inhibitory control was measured with a Stroop task, set-shifting with a verbal fluency task, and creativity with a divergent thinking task. The number of perceptual switches increased in all four tasks between 6 and 10 years of age, but differed across tasks in that it was higher in the verbal transformation and ambigous structure-from-motion tasks than in the ambigous figure and auditory streaming tasks for all age groups. Although perceptual switching rates differed across tasks, there were predictive relationships between switching rates in some tasks. However, little evidence for the influence of central processes on perceptual switching was found. Overall, the results support the notion that perceptual switching is largely modality- and task-specific and this property is already evident when perceptual switching emerges.

Keywords: perceptual bistability; visual bistability; auditory bistability; perceptual switching; executive functions; creativity.

The complex and dynamic natural world that we inhabit presents our sensory systems with a challenging problem; namely, the decomposition of continuous streams of sensory input into stable and veridical representations of objects in the environment around us. One paradigm that has been used to study the perceptual strategies employed by our sensory systems is perceptual bistability, the phenomenon in which perception switches between alternative interpretations of an unchanging ambiguous stimulus. There are many, qualitatively different, ways to elicit perceptual bistability, and it has been reported in vision, audition and even olfaction (Kleinschmidt, Sterzer, & Rees, 2012). The ambiguities inherent in perception have recently been brought to public attention through social media spreading of examples of perceptual ambiguity in the visual ('blue/black versus white/gold' dress) and auditory ('yanny/laurel') domains (Lafer-Sousa, Hermann, & Conway, 2015; Watson, 2018). These viral phenomena have highlighted gaps in our knowledge concerning why people perceive stimuli in different ways, and how individual differences in the ability to perceive different interpretations of a stimulus emerge (Lafer-Sousa et al., 2015). The ability to explore multiple ways of parsing the sensory scene and to flexibly switch between alternatives are thought to be prerequisites of cognitive flexibility, creativity, imagination and perspective taking (Bialystok & Shapero, 2005; Wiseman et al., 2011).

Perceptual switching is typically experienced through prolonged exposure to a stimulus which itself is unchanging yet has more than one viable interpretation. The 'correct' interpretation of the stimulus is therefore ambiguous. The ability to perceptually switch develops from the age of 4 years onwards in both vision and audition (Sussman, Wong, Horvath, Winkler, & Wang, 2007; Wimmer & Doherty, 2011). For example, between 4 and 5 years children begin to perceive both interpretations of the duck/rabbit ambiguous figure, provided the child is first informed about the two interpretations (Doherty & Wimmer, 2005; Gopnik & Rosati, 2001; Mitroff, Sobel, & Gopnik, 2006; Rock, Gopnik, & Hall, 1994;

Wimmer & Doherty, 2011; Wimmer & Marx, 2014) and between 5- and 9-years when uninformed (Mitroff et al., 2006). By 6 years children spontaneously perceive multiple interpretations in verbal transformation tasks (e.g., repeated presentation of the non-word "flime" results in perception typically switching back and forth between "flime" and "clime") (Warren & Warren, 1966). Regarding the auditory streaming paradigm, the ability to switch depends on the pitch difference between low and high tones, with 5-11-year-old children requiring larger differences than adults to perceive the two dominant alternative interpretations (Sussman et al., 2007). Thus, the ability to switch interpretations develops between 4- and 6 years but the specific developmental trajectory may be task and modality specific. This possibility has not yet been explored as to date no comparison across tasks and modalities has been conducted within the same developmental sample. An important theoretical question is whether the processes underlying perceptual switching in the visual and auditory domain are domain specific or domain general (Denham et al., 2018; Pressnitzer & Hupé, 2006). In the current research we adopt a developmental approach including 6- to 10-year-old children to allow examining the question of domain generality or specificity in visual and auditory switching.

Here we distinguish between the ability to perceive more than one interpretation (ability to switch) and the rate of ongoing perceptual switching between the alternatives, given that the basic ability to switch exists. As typical phase durations are rather long, instead of analysing switching rate (switches per second – a very small quantity), we consider the mean number of switches within a given duration (here 60 seconds) as a proxy for switching rate. Preliminary evidence from the verbal transformation task suggests that even after the ability to switch has developed there are ongoing developmental increases in switching rate between 6 and 10 years, and 10 years and adulthood (Warren & Warren, 1966). Additionally, for ambiguous structure-from-motion tasks, the rate of switching increases between 10 years

and young adulthood (Ehlers, Struber, & Basar-Eroglu, 2016), suggesting that the mechanisms underlying perceptual switching undergo further maturation after the ability to switch has developed.

There are several reasons to expect changes in switching rate between 6- and 10 years. In the visual domain, even though important perceptual functions emerge in the first years of life, there are ongoing developments, such as shifts from feature processing styles predominant until 4 years to increasingly global processing by 7 years (Nayar, Franchak, Adolph, & Kiorpes, 2015). Susceptibility to visual illusions, such as the Ebbinghaus illusion increases with age, particularly between 4- and 10 years (Bremner et al., 2016; Doherty, Campbell, Tsuji, & Phillips, 2010), suggesting a default local processing style in younger children changing to a more global processing style in older children. Feature versus global processing in adults has been shown to affect ambiguous perception and switching rate (Gale & Findlay, 1983; Long & Toppino, 2004). Thus, switching rate might change after the ability to switch has developed due to changes in perceptual processing (Doherty et al., 2010). However, it remains unclear what specific mechanisms determine the rate of perceptual switching in children. While inhibitory control is associated with the ability to switch (Wimmer & Doherty, 2011; Wimmer & Marx, 2014), its influence on the rate at which perception switches has not been explored in children. For instance, in adults inhibitory control measured with a Stroop task was found to be negatively related to switching rates in the auditory streaming task (Farkas, Denham, Bendixen, Tóth, et al., 2016), while no such relation was found in the Necker cube task (Díaz-Santos et al., 2017). Thus, in adults the relation between inhibitory control and switching rate is inconsistent. In children, the relation has not yet been investigated.

Another executive function of potential relevance is set-shifting, the ability to switch between tasks or mental sets (Miyake et al., 2000), something that has been shown to relate to

6-year-olds' ability to experience alternative interpretation of ambiguous figures when prompts and biased interpretations are provided (Bialystok & Shapero, 2005). However, the evidence is again inconclusive. Set-shifting does not relate to 4- and 5-year-olds' ability to perceptually switch *per se* (Wimmer & Doherty, 2011) nor does it relate to perceptual switching rates in ambiguous structure-from-motion (Chamberlain, Swinnen, Heeren, & Wagemans, 2017) or auditory streaming (Farkas, Denham, Bendixen, Tóth, et al., 2016) tasks. Measuring both inhibitory control and set-shifting in this study together with a range of ambiguous tasks may allow us to address some of the inconsistencies in the current literature.

Executive functions have been also found to be associated with creativity (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Gonen-Yaacovi et al., 2013; Sharma & Babu, 2017). Creativity, as measured with the Pattern Meanings task (Wallach & Kogan, 1965), is positively correlated with the perceptual switching in the vase-face and Necker cube tasks in 16-18-year-olds (Doherty & Mair, 2012). A positive association is also evident in adults between divergent thinking and perceptual switching in the duck-rabbit task (Wiseman, Watt, Gilhooly, & Georgiou, 2011). These results suggest that subjective experience of perceptual switching may be related to discovering new solutions in creativity tasks (Schooler & Melcher, 1995). In contrast, Farkas, Denham, Bendixen, Tóth, et al. (2016) found no correlation between divergent thinking measures of creativity and perceptual switching in the auditory streaming task in adults. Differences in perceptual tasks and measures of creativity make it difficult to draw any conclusions regarding the relation between creativity and perceptual switching and no previous study has explored the link between creativity and perceptual switching rates in children.

In sum, we offer the first systematic investigation of perceptual switching behaviour in response to ambiguous stimuli in 6-, 8- and 10-year olds across different tasks and modalities (two visual and two auditory tasks). We anticipate that the number of switches

(switching rate) will increase with age on the verbal transformation task based on preliminary evidence (Warren & Warren, 1966) but it is unclear whether this will generalise to the other tasks tested here. If perceptual switching depends upon general maturational processes and general perceptual processing styles as previously found in perceptual illusions (Bremner et al., 2016; Doherty et al., 2010; Nayar et al., 2015) then we would expect to find the same age effects across all ambiguous perception tasks. If perceptual switching is consistently related to executive functions or creativity this would suggest a domain-general aspect to the development of a flexible perceptual system. If there is no systematic relation then this would speak for separate, yet generic, task-specific systems underlying perceptual switching (Denham et al., 2018).

Method

Participants

Overall, 66 children (28 girls, 38 boys) from a local state-funded primary school took part in the study. Children were predominately Caucasian native English speakers, coming from a mix of socioeconomic backgrounds. There were 22 6-year-olds (M = 72 months, SD = 4), 23 8-year-olds (M = 96, SD = 4), and 21 10-year-olds (M = 123, SD = 3). Participants had parental consent and gave their assent on the day of testing.

Design

Each child performed 9 tasks: Four perceptually ambiguous tasks: ambiguous figure, ambiguous motion, verbal transformation, auditory streaming, and a visual and auditory control task. Additionally, the Day-Night Stroop task (inhibition), pattern meanings (creativity), and verbal fluency (set-shifting) tasks were administered.

Materials and Procedure

Children were seen individually in two 30 minutes sessions in a quiet room in their school. They sat at approximately 60 cm distance from a Dell Latitude E6520 computer (15"

monitor with 1600 x 900 resolution). Sounds were presented binaurally through headphones (Sony, MDRNC7B) adjusted to a comfortable volume. The experimenter sat next to the child and reminded children to focus on their task. Unlike in adult research where head movement is constrained, the children were simply asked not to move their heads and to look at the screen. Task order was counterbalanced within and between sessions with the constraint that perceptual tasks from the same modality (e.g., visual) never followed each other.

Perceptually ambiguous tasks. The *ambiguous figure task* (Jastrow, 1899) (Figure 1 upper left panel) depicted an ambiguous line drawing (7.7 x 5 cm), subtending 4.81 × 7.2 (v × h) degrees of visual angle. Participants were asked to report whether they perceived a duck or a rabbit. The body of the duck and rabbit were added to the ambiguous head during the disambiguation (training) phase.

The *ambiguous structure-from-motion task* (Wallach & O'Connell, 1953) (Figure 1, lower left panel), consisted of a revolving cylinder with two transparent layers of 200 randomly positioned white dots over a black background, moving in opposite directions with a sinusoidal speed profile (Klink et al., 2008). The cylinder subtended 5.11 × 6.15 (v × h) degrees of visual angle. A single dot was 12.29 × 12.35 arcmin (v × h) and moved with a peak angular speed of 6.96 degrees/second. Participants were asked to report whether they perceived the front face of the cylinder moving left- or rightwards. Disambiguated versions were created by dimming the luminance of either the leftward or rightward moving dots.

The sound used in the *verbal transformation task* (Warren & Gregory, 1958*)* (Figure 1, upper right panel), was the word "life", spoken by a native female English speaker. Word duration was 0.39 seconds, mean pitch 203 Hz. To create the ambiguous stimulus, the word was looped without pause 153 times. Participants were asked to report whether they heard the word "life" or "fly". For disambiguation, the words "life" and "fly" were presented once.

The *auditory streaming task* (van Noorden, 1975) (Figure 1, lower right panel), was a sequence of a repeating low-high-low pitched sounds (LHL_), where "L" and "H" were complex sounds and "_" indicates a silence with the same duration as the sounds. The sound "L" was a recording of a water droplet hitting glass (a wine glass), and the sound "H" was a recording of a water droplet hitting ceramic (china cup). The pitch difference between the two sounds was 28 Hz, with a mean pitch of L, 402 Hz (range 397 - 408 Hz) and H, 430 Hz (range 428 - 431Hz). Stimulus onset asynchrony (SOA, onset to onset time interval) was 150 milliseconds. In general, a trade-off between the frequency difference (Δf) and stimulus onset asynchrony (SOA) between the H and L tones determines whether people hear the sounds primarily as originating from a single source (or stream) or two separate sources. When Δf is very small (< 1 semitone: ST), participants always perceive the sounds as coming from a single source. When Δf increases (> 4 ST), and/or SOA decreases the L and H tones are more likely be heard as coming from two separate sources (van Noorden, 1975) and it has been found that over a very wide range of parameters, both interpretations may be experienced (Denham, Gyimesi, Stefanics & Winkler, 2013), making the stimulus ambiguous.

Participants were asked to report whether they perceived one dripping tap or two dripping taps. For disambiguation, participants were shown a picture and sound of one tap and two taps. The one tap sound contained three water droplets falling from the tap once all of equal intensity; i.e., one LHL_ cycle. The two tap sound contained a 19 dB intensity difference between "L" and "H" sounds: L = 76 dB, H = 57 dB, to emphasize the perceptual pop-out of the L sound. Children had to close their eyes and report what they heard (i.e., one or two taps).

All test and training stimuli can be found in the supplementary material.

Training proceeded as follows: 1) the ambiguous stimulus was presented for 15 seconds, after which children were asked what they saw or heard; 2) the stimulus was

disambiguated until children understood the two possible categories; 3) the ambiguous stimulus was presented again (Figure 1). Prior to the test phase, participants were instructed on which buttons they should use to indicate what they saw/heard. Testing proceeded once the children understood the perceptual categories, the button assignments, and the task they were to perform.

Test phase. Children were instructed to keep the buttons pressed as long as they perceived one interpretation and to switch to the other button as soon as their perception changed. Button boxes were on the right and left sides of the table, with pictures of the disambiguated interpretations attached. Category position (left/right) assignment was randomized across participants except for the ambiguous motion task in which it was kept constant (left right). The program recorded the button presses from which the *number of switches* were calculated for each participant.

For each task, three 60-seconds blocks were separated by a pause. Participants performed the other non-perceptual tasks between the four perceptual tasks.

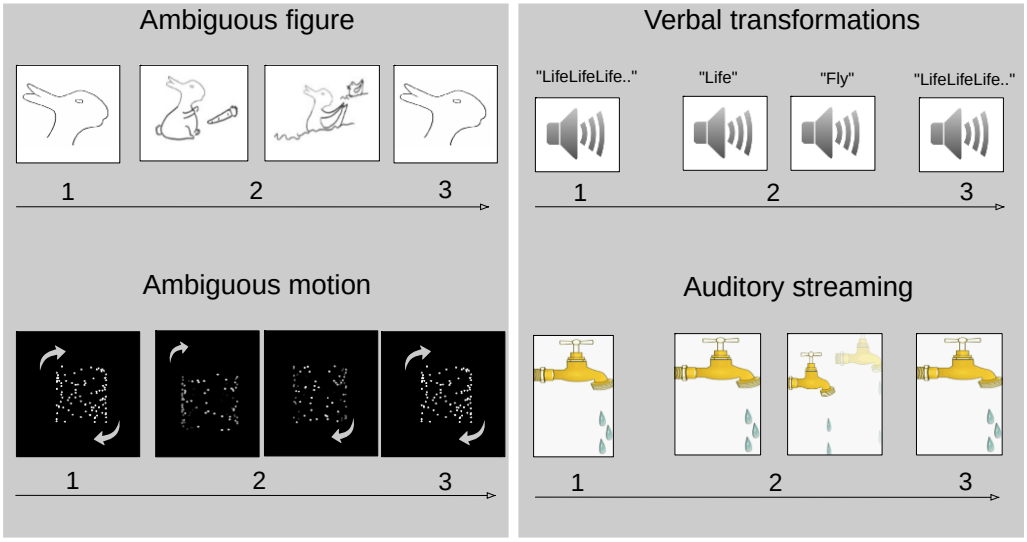

Figure 1. Stages for each perceptual task: 1) Initial perception of an ambiguous stimulus; 2) Disambiguation of two perceptual alternatives; 3) Ongoing perception of the ambiguous stimulus during the test phase.

Perceptual control tasks. One visual and one auditory control task were administered to ensure that the children followed instructions.

In the *visual control task*, children looked at an unambiguous picture (drawing of a girl) for 60 seconds and a morphing animation (a horse morphed into a sheep) for 60 seconds. They were instructed to press a key on the keyboard whenever they saw the picture changing. Children were excluded from the analyses if they reported a change in the unambiguous picture or if they did not report any change in the morphing animation. Two participants were removed from the final analyses for failing this task (see Results).

In the *auditory control task* children listened to two 30-second sound segments, both consisting of the two interleaved dripping taps, but one segment having the disambiguated form (intensity difference), and the other the ambiguous form; segment order was randomised across participants. Participants were required to report the correct perceptual category, as instructed during training. One participant was excluded for failure in this control task (see Results).

Stroop task. Inhibition was measured using a Day-Night Stroop task (Simpson & Riggs, 2005). Two pictures with a day and a night scenario were presented (Figure 2); children were required to press a dark blue button in response to the day scenario and a yellow button for the night scenario. Participants had a pre-test phase where they could practice the task. During the test phase, 16 pictures were presented in a pseudo-random order - DNNDNDDNNDNDDNDN (8-day and 8-night pictures), and participants were asked to respond as accurately and quickly as possible. Each picture was presented for a maximum of eight seconds with a two-second inter-trial interval. Accuracy and reaction times were recorded.

Stroop Memory Control. To measure basic working memory components of the Stroop task (i.e., remembering what button to press for which picture) participants saw two abstract images (Figure 2) and pressed the associated dark blue or yellow button. Otherwise, the procedure was the same as above. To isolate the inhibition component of the task, mean time in the memory control task (memory RT) was subtracted from mean reaction time in the Stroop task (Stroop RT) to yield inhibition RT.

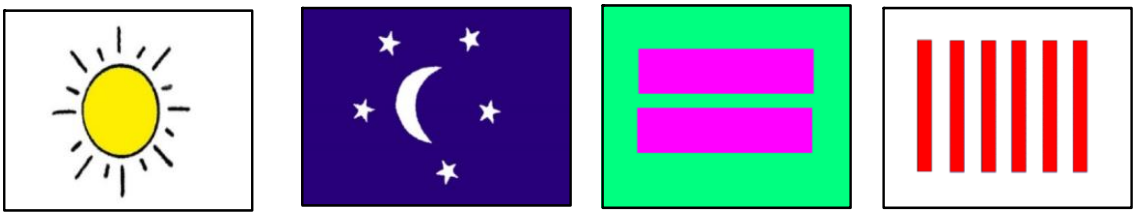

Figure 2. Images used in the Stroop task (two leftmost images) and the related memory control task (two rightmost images).

Pattern meanings task. Creativity was assessed using the pattern meaning task of Wallach and Kogan (1965), which is a divergent thinking test. Eight abstract patterns were presented individually on 20 × 14 cm laminated cards (Figure 3). Children were asked to describe "all the things you think it could be or that it reminds you of". The main variable of interest was the total number of responses generated by each participant (cTotal). Two independent raters coded 30% of the data to determine interrater reliability. Cohen's kappa test showed good agreement between the two raters, cTotal, $\kappa = .854$ (95% CI, .704 to 1.00), $p < .001$. As interrater agreement was very good, only one of the raters coded the remaining 70% of the data.

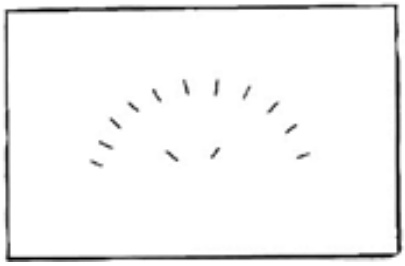

Figure 3. Example of a pattern used in the pattern meanings task.

Verbal fluency task. Set-shifting was measured using a verbal fluency task (Troyer, Moscovitch, & Winocur, 1997). Children had 60 seconds to name as many animals they could think of, "please tell me as many animals as you can" (semantic fluency), or to name words that start with the letters F, A, and S (phonetic fluency). The order of the four verbal fluency subparts (F, A, S, animals) was randomized across participants. Responses were recorded using a digital voice recorder. The responses for each of the four test subparts were transcribed and words belonging to the same category were determined. For example, if in response to the animal naming task participants generated the words: "cat", "dog", "octopus", "fish", the first two words were considered part of one category (i.e., domestic animals) and the last two words part of a second category (i.e., aquatic animals). Similarly, if in response to the letter F naming task participants responded with "fish", "finish", "focus", the first two words were considered part of one category (i.e., words that start with the letters "fi-" and the last word was considered part of the beginning of another category (i.e. words that starts with "fo-"). The total number of switches between categories (VF switch) was the dependent measure for set-shifting. Two independent raters coded 30% of the data to determine interrater reliability; Cohen's kappa test, VF switch, $\kappa = .847$ (95% CI, .691 to 1.00), $p < .001$. As the agreement between the two raters was very good, only one person coded the remaining 70% of the data.

Data analysis

To examine both the ability to switch and the number of switches in the perceptual bistability tasks, two 3 x 4 (age group: [6- vs. 8-vs. 10-year-olds] x tasks: [ambiguous figure vs. ambiguous motion vs. verbal transformation vs. auditory streaming]) repeated measures ANOVAs were computed with task as a within participant variable and age group as a between participants variable. Performance on the Stroop, pattern-meanings, and verbal fluency tasks was examined using several univariate ANOVAs with age group as a between

participants variable. Bonferroni post-hoc tests were used throughout. For simplicity, after reporting the results from ANOVA, whenever we used multiple pairwise t-test comparisions we report only the lowest t-value for all significant effects, with plural indicated by appending an 's', e.g. *t*s ≥ 6.71, *p*s < .001. We used linear regression to examine factors predicting the number of perceptual switches in each task.

Results

Three participants (two 6-year-olds, one 8-year-old) were excluded from the final analyses for failure in the auditory and visual control tasks.

Perceptually ambiguous tasks: Ability to switch

For comparison with the developmental literature in ambiguous perception, we first examined whether children aged 6-10 years would be able to switch at all (yes = 1/ no = 0; see Figure 4). The ability to switch was statistically different from zero across all four tasks for all age groups, *t*s ≥ 6.71, *p*s < .001.

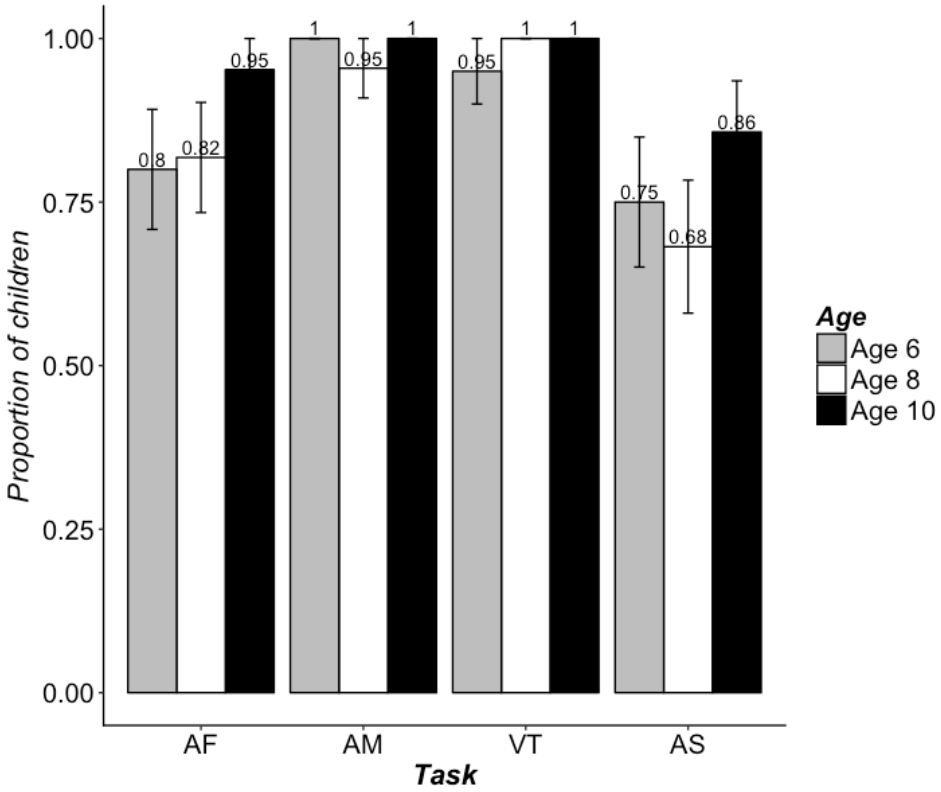

Figure 4. Proportion of children able to switch. Mean pass/fail scores for each perceptual task for each age group. Error bars show standard errors of means. AF = ambiguous figure, AM = ambiguous motion, VT = verbal transformation, AS = auditory streaming.

There was no effect of age on pass/fail switching scores, $F(2, 60) = 2.181$, $p = .12$, $\eta_p^2 = .07$; 6-year-olds ($M = .88$) were equally able to switch as 8-year-olds ($M = .86$, $p = 1.00$) who in turn were equally able to switch as10-year-olds ($M = .95$, $p = .17$). There was a difference in the ability to switch across tasks ($F(3, 180) = 8.74$, $p < .001$, $\eta_p^2 = .13$).

Post-hoc comparisons showed that the mean proportion of participants able to perceptually switch varied for the different tasks as follows: ambiguous motion ($M = .99$), ambiguous figure ($M = .86$), auditory streaming ($M = .76$), verbal transformations ($M = .98$), with significant differences between the ambiguous figure and ambiguous motion tasks ($p = .022$), between the ambiguous motion and auditory streaming tasks ($p = .002$), and between the verbal transformation and auditory streaming tasks ($p = .002$). No other differences were significant ($p > 0.05$).

Perceptually ambiguous tasks: Number of Switches

The mean number of switches across participants is summarised in Figure 5 for each of the three blocks, separately for each age group.

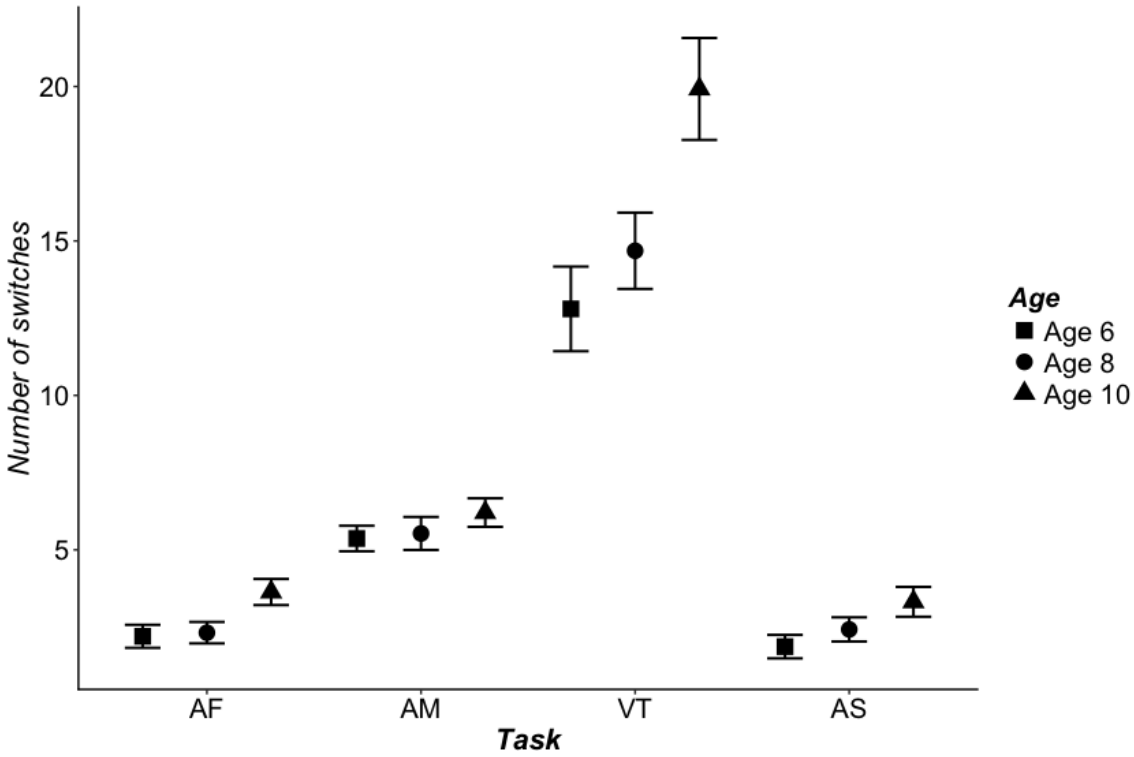

Figure 5. Number of Switches. The mean number of switches for each task and for each age group. Error bars show standard errors of means. AF = ambiguous figure, AM = ambiguous structure-from-motion, VT = verbal transformation, AS = auditory streaming.

The number of switches increased with age, $F(2, 60) = 4.06$, $p = .022$, $\eta_p^2 = .12$, where 6-year-olds ($M = 16.68$) reported fewer switches than 10-year-olds ($M = 24.81$, $p = .025$). Eight-year-olds ($M = 18.72$) did not differ in their number of switches from either age group ($ps > .12$). The number of switches also differed across tasks, $F(3, 180) = 98.43$, $p < .001$, $\eta_p^2 = .62$, where more switches occurred in the verbal transformation task ($M = 47.40$) than all other tasks ($ps < .001$). There were also more switches in the ambiguous motion task ($M = 17.10$) than both ($p < .001$) the ambiguous figure ($M = 8.15$) and auditory streaming tasks ($M = 7.61$) which did not differ ($p = 1.00$). There was no age group x task interaction, $F(6, 180) = 1.95$, $p = .08$, $\eta_p^2 = .06$.

Inhibition, creativity, and set-shifting

A summary of performance on the Stroop, pattern meanings, and verbal fluency tasks is presented in Table 1 below.

Table 1. Mean task performance for each age group (standard deviation in parentheses)

Task	Measure	6-year-olds (N = 20)	8-year-olds (N = 22)	10-year-olds (N = 21)
Stroop	Stroop RT	1444 (415)	1086 (312)	886 (280)
	Memory Control RT	1141(292)	968 (241)	722 (220)
	Inhibition RT	303 (347)	117 (445)	164 (162)
Pattern meaning	cTotal	19.25 (5.24)	24.41 (8.98)	23.24 (8.85)
Verbal fluency	VF switches	5.85 (3.56)	9.05 (2.70)	9.67 (3.54)

Note. Reaction times (RT) are displayed in milliseconds; Inhibition RT = Stroop RT - Stroop memory control RT.

Stroop task. Accuracy on the Stroop task was at ceiling across all age groups (6-year-olds: M = .90, 8-year-olds: M = .93, 10-year-olds: M = .95) therefore no further statistical analyses were conducted on accuracy.

Stroop response time decreased with increasing age ($F(2, 62) = 14.23$, $p < .001$, $\eta_p^2 = .32$), particularly between adjacent ages of 6- and 8-years ($p = .003$) but not between 8- and 10-years ($p = .17$). Memory control response time also decreased with increasing age ($F(2, 62) = 14.40$, $p < .001$, $\eta_p^2 = .32$), particularly between adjacent ages of 8- and 10-years ($p = .006$) but not between 6- and 8-years ($p = .09$). There was no effect of age on inhibition (Stroop RT – memory control RT) ($F(2, 62) = 1.66$, $p = .20$, $\eta_p^2 = .05$).

Pattern meanings task. The total number of responses, cTotal, did not differ with age ($F(2, 62) = 2.40$, $p = .10$, $\eta_p^2 = .07$).

Verbal fluency. The number of category switches, VF switches, increased with increasing age ($F(2, 62) = 7.95$, $p < .001$, $\eta_p^2 = .21$), especially between 6- and 8-years ($p = .008$) but not between 8- and 10-years ($p = 1$).

Correlations between inhbition, creativity, set-shifting, and age

Correlations were calculated between the Stroop inhibitory control measure, pattern meaning test overall performance age, and number of switches in the verbal fluency task (Table 2). Age only correlated with the number of switches in the verbal fluency task. After partialling out age, performance in the pattern meanings task correlated with the number of switches in the verbal fluency task.

Table 2. Correlations between age, executive functions, and creativity. Correlations above the diagonal and partial correlations (partialling out age) below the diagonal between the Stroop, pattern meaning, and verbal fluency tasks.

	Inhibition	Creativity Total	Verbal fluency Switch
Age	-.21	.20	.42***
Inhibition	---	.08	-.01
Creativity Total	.13	---	.48***
Verbal fluency Switch	.08	.45***	---

Note: *** $p < .001$.

Predictors of the number of perceptual switches in the ambiguous tasks

Four linear regression analyses were conducted to investigate whether the number of switches in each perceptual task was predicted by the number of switches in the other

perceptual tasks, age group, inhibition (Stroop inhibitory control), set-shifting (verbal fluency) and creativity (pattern meaning test). All variables were introduced in one step. There was no multicollinearity in any of the models and the variance of the inflation factor was less than 2.0.

The regression models were significant for the number of perceptual switches in the ambiguous figure task, R^2 = 35.1%, $F(7, 55) = 4.25$, $p = .001$, verbal transformation task, R^2 = 36.4%, $F(7, 55) = 4.49$, $p = .001$, and auditory streaming tasks, R^2 = 46.9%, $F(7, 55) = 6.93$, $p < .001$. The model was not significant for the number of switches in the ambiguous motion task, R^2 = 6.8%, $F(7, 55) = .575$, $p = .77$ (Tables 3-6).

The number of switches in the ambiguous figure task was predicted by the number of switches in auditory streaming (Table 3). The number of switches in the verbal transformation task was predicted by the number of switches in auditory streaming and pattern meaning performance (Table 5). The number of switches in auditory streaming was predicted by the number of switches in ambiguous figure and verbal transformation tasks (Table 6). There were no further significant predictors.

Table 3. Regression analysis for the number of switches in the ambiguous figure task

Independent Variables	*B*	*b SE*	*β*	*t*
Age group	.55	.57	.12	.97
Number of switches in AM	.08	.09	.10	.88
Number of switches in VT	-.03	.03	-.14	-1.03
Number of switches in AS	.44	.10	.58	4.53***
Inhibition	.00	.00	.08	.75
Creativity	.08	.12	.09	.67
Set-shifting	.19	.27	.09	.69

Note: *** $p < .001$. t = t tests coefficient, b = unstandardized beta coefficient, b *SE* = standard error for b, β = standardized beta coefficient. AM = ambiguous structure-from-motion, VT = verbal transformation, AS = auditory streaming.

Table 4. Regression analysis for the number of switches in the ambiguous motion task

Independent Variables	*b*	*b SE*	*β*	*t*
Age group	.09	.86	.02	.10
Number of switches in AF	.18	.20	.154	.88
Number of switches in VT	.02	.05	.07	.45
Number of switches in AS	-.16	.17	-.17	-.95
Inhibition	.00	.00	-.04	-.26
Creativity	.10	.18	.09	.57
Set-shifting	.29	.41	.11	.70

Note: t = t tests coefficient, b = unstandardized beta coefficient, b *SE* = standard error for b, β = standardized beta coefficient. AF = ambiguous figure, VT = verbal transformation, AS = auditory streaming.

Table 5. Regression analysis for the number of switches in the verbal transformation task

Independent Variables	*b*	*b SE*	*β*	*t*
Age group	3.33	2.22	.19	1.50
Number of switches in AF	-.55	.53	-.14	-1.03
Number of switches in AM	.16	.35	.05	.46
Number of switches in AS	1.55	.40	.50	3.81***
Inhibition	-.00	.01	-.02	-.18
Creativity	.94	.45	.26	2.06*

Set-shifting	.30	1.14	.04	.26

Note: *** $p < .001$, * $p < .05$, $t = t$ tests coefficient, b = unstandardized beta coefficient, b *SE* = standard error for b, β = standardized beta coefficient. AF = ambiguous figure, AM = ambiguous structure-from-motion, AS = auditory streaming.

Table 6. Regression analysis for the number of switches in the auditory streaming task

Independent Variables	b	b *SE*	β	t
Age group	-.10	.68	-.01	-.14
Number of switches in AF	.62	.14	.47	4.50***
Number of switches in AM	-.10	.11	-.10	-.95
Number of switches in VT	.14	.04	.42	3.81***
Inhibition	.00	.00	-.11	-1.23
Creativity	-.03	.14	-.03	-.21
Set-shifting	-.25	.33	-.10	-.77

Note: *** $p < .001$. $t = t$ tests coefficient, b = unstandardized beta coefficient, b *SE* = standard error for b, β = standardized beta coefficient. AF = ambiguous figure, AM = ambiguous structure-from-motion, VT = verbal transformation.

Discussion

This is the first investigation of perceptual switching across four different tasks (two auditory and two visual) within the same developmental sample. In line with separate strands of evidence from visual (duck/rabbit ambiguous figure task) and auditory (verbal transformations, auditory streaming) tasks (Sussman et al., 2007; Warren & Warren, 1966; Wimmer & Doherty, 2011), our current findings indicate that the ability to switch *per se* is present from the age of 6 across all tasks tested, thus, applying to multiple tasks and domains.

However, this ability varies across individuals and tasks. In addition, the rate of perceptual switching increases between 6 and 10 years of age, and this was the case in all four tasks. As the increase in perceptual switching rate with age is not task or domain specific, this suggests a role for generic maturational processes too.

A long-standing question in perceptual bistability has been whether perceptual switching is caused by domain specific or domain general mechanisms. Our results in this developmental study are consistent with recent findings in adults (Denham et al., 2018) which showed that while many properties of perceptual switching are very similar across tasks and modalities, spontaneous perceptual switching is not centrally controlled.

Overall, our findings indicate task specific rather than domain specific (i.e., vision and audition) differences. Perceptual switching rates in the verbal transformation task were far higher than in any of the other tasks, and this was the only task that used concrete objects that children would have encountered prior to the experiment. Language specific processing evident early in development leads to strong representations for words. For example, from 6-months onwards infants can already extract word forms from natural speech (Saffran, Aslin, & Newport, 1996), and these strong representations have been associated with faster retrieval and processing for words than, for example, simple tones (Rayner & Clifton, 2009). Modelling studies have shown that switching rate increases with the strength of the competing interpretations (Mill, Bőhm, Bendixen, Winkler, & Denham, 2013). Therefore, since children in our current age range would have already encountered the words "life" and "fly" frequently (Stuart, Masterson, Dixon, & Quinlan, 1993-1996), we suggest that prior experience, and hence stronger representations, may explain the far greater number of switches reported in the verbal transformation task than any of the other tasks. In contrast, it is highly unlikely that the children would have heard the temporal patterns caused by the dripping taps in the auditory streaming task or would have seen randomly positioned moving

dots forming a rotating cylinder, before the experiment. Therefore, the explanation also accounts for the far smaller number of perceptual switches reported in these tasks. The intermediate number of switches reported in the duck/rabbit task may similarly be accommodated. In this case, while the children were undoubtedly familiar with ducks and rabbits, they may not have seen the line drawing versions of these animals before. Thus, while the concepts were clear, the stimulus may not have mapped very well onto the childrens' internal representations of ducks and rabbits; hence, reducing the number of perceptual switches. Our data are consistent with previous findings that prior knowledge and familiarity with the stimuli can exert top-down influences on perceptual switching (Long & Toppino, 2004; Rock, et al., 1994). Future research may want to control for familiarity, e.g. using an equally unfamiliar verbal transformation stimulus, such as a non-word, and examine the effect of familiarity on switching rates.

The regression analyses showed that although there are clearly task specific processes at work, nevertheless there is also some commonality in perceptual switching rates across tasks. In the current experiment, participants' switching rate in auditory streaming mutually predicted switching rates in the ambiguous figure and verbal transformation tasks. Therefore, it could be argued that some process related to the auditory streaming task is common to the ambiguous figure and verbal transformation tasks. However, the negative relationship between ambiguous figure and verbal transformation switching rates argues against the common process explanation. Based on findings in adults of strong correlations between perceptual switching rates in different tasks in the presence of evidence that different processes underlie switching in the different tasks, Denham and colleagues (2018) argued for common principles implemented by independent processes. The current findings are compatible with this view. Age was not a significant predictor for switching rate in the individual tasks, providing additional support for the notion that task specific rather than

generic developmental changes are involved in early perceptual switching. The influence of more central cognitive processes on perceptual switching rates in each of the tasks was generally negligible, except for the prediction of switching rate in the verbal transformation task by creativity. This too is consistent with the patchy results from the adult literature. Based on these results and similar findings in adults we suggest that the most likely explanation is that task-specific (distributed, yet generic), properties of the neural circuitry give rise to the observed task-dependent dynamics of perceptual switching (Hupé, Joffo, & Pressnitzer, 2008; Pressnitzer & Hupé, 2006). These properties differ across individuals and mature through development.

One possible explanation for the developmental increase in switching rate is that the fronto-parietal brain circuitry, putatively involved in the switching process (Brascamp, Kanai, Walsh, & van Ee, 2010; Brascamp, Sterzer, Blake, & Knapen, 2018; de Graaf, de Jong, Goebel, van Ee, & Sack, 2011), undergoes a maturational process (see also Dekker et al., 2017; for higher-level processing developments in 6-12-year-olds; Ehlers et al., 2006). In a recent study of the neurobiological mechanisms underlying the effect of aging on perceptual rivalry, Arani, van Ee, and van Wezel (2018) argued that the age-dependent decrease in perceptual switching rates in the elderly may be caused by changes in neural adaptation and neural noise. Consistent with these ideas, there is evidence of a developmental increase in neuronal noise in children, argued to be an indicator of an increase in the complexity of the neural circuitry (McIntosh et al., 2010). Most computational models of perceptual switching (e.g., visual: Brascamp, van Ee, Noest, Jacobs, & van den Berg, 2006; auditory: Mill et al., 2013) depend upon noise, or more precisely a balance between noise and adaptation (Shpiro, Moreno-Bote, Rubin, & Rinzel, 2009), in order to simulate the dynamics of perceptual switching and there is some neurobiological evidence for a necessary role for neuronal noise in perceptual switching (e.g., see van Ee, 2009). Therefore, one possible explanation for the

developmental increase in switching rate is an increase in the complexity of the neuronal circuitry and concomitant increase in neuronal noise.

The change in switching rate with age might also be linked to changes in both the ability to sustain attentional focus on the competing interpretations, as well as in local and global aspects of perceptual processing strategies. Sustained attention matures during primary school (Betts, Mckay, Maruff, & Anderson, 2006; Lin, Hsiao, & Chen, 1999). Attentional focus over the two competing alternating interpretations in perceptual bistability influences switching rate in vision (Denham et al., 2018; Intaitė, Koivisto, & Castelo-Branco, 2014), in audition (Denham et al., 2018; Farkas, Denham, Bendixen, & Winkler, 2016), as well as in multisensory perception (van Ee et al, 2009; Alais, van Boxtel, Parker, & van Ee, 2010). In other words, changes in attentional focus may provide a possible explanation for changes in switching rate with age.

In addition, perceptual switching may involve processes that undergo development until late adolescence and are associated with changes in perceptual processing style (Plude, Enns, & Brodeur, 1994; Porporino, Iarocci, Shore, & Burack, 2004). Perceptual processing may move gradually from feature-based processing to global processing (van Ee, 2011). The suggestion is that when two full (global) figures compete with one another as opposed to small local competing features (which may drive patch-wise alternation, but not a switch between two full figures) then perceptual switching is faster. There is evidence for this change, at least in the perception of visual illusions (Bremner et al., 2016; Káldy & Kovács, 2003; Nayar et al., 2015) and processing style has been previously associated with switching rate (Long & Toppino, 2004). However, we did not investigate children's processing style or attentional focus, establishing the validity of these explanations requires further investigation.

Prior evidence relating executive and higher level functions with perceptual switching has been inconsistent. While inhibitory control has been shown to underlie the ability to

switch in 4- and 5-year-olds (Wimmer & Doherty, 2011; Wimmer & Marx, 2014), in this study using slightly older children we found no evidence relating inhibitory control and switching rate, consistent with previous reports for adults (Denham et al., 2018; Díaz-Santos et al., 2017; Farkas et al., 2016). Similarly, set-shifting was not related to switching rate, in line with previous auditory streaming studies in adults (Farkas, Denham, Bendixen, Tóth, et al., 2016; Farkas, Denham, & Winkler, 2018), ambiguous structure-from-motion (Chamberlain et al., 2017) and the Necker cube (Díaz-Santos et al., 2017). Overall, our study provides no evidence that either executive function (inhibition, set-shifting) is related to switching rate in childhood. The only association between the perceptual tasks and central measures that remained significant after controlling for the effects of age, was between verbal transformations and creativity. This could be due to the nature of the tasks, both relying on verbal processing. Similar patchy findings have been reported in the adult literature; while Doherty and Mair (2012) found a relation between pattern meaning performance and perceptual switching in both Rubin's vase-faces and Necker cube tasks, Denham et al. (2018) found no correlation between self-reports of creativity and switching rate in either the ambiguous structure-from-motion or auditory streaming tasks. Thus, our findings are in line with the contradictory evidence in adults, suggesting that the link between creativity and perceptual switching is somewhat dubious.

This study has a number of limitations. Questions such as whether perceptual switching is related to the ability to sustain attentional focus or to perceptual processing style were not explored, leaving uncertainty over their possible role in this process. Another limitation is that creativity, set-shifting, and inhibitory control were assessed using only one measure for each. Although the measures used were selected based on previous findings in the literature, in the light of the task-dependent differences in perceptual switching shown in this study, it may be advisable in future research to implement a battery of tests to

characterise each of these central factors to explore the specificity of the links between perceptual switching and different creativity and executive function measures.

In conclusion, the present study has shown that the rate of perceptual switching increases between 6 and 10 years of age across a range of visual and auditory perceptual bistability tasks. Similar to adults, the results indicate that perceptual switching has task specific characteristics, and these characteristics are already evident in childhood. Overall, these results show that perceptual flexibility is an inherent property of the perceptual system from very early on. Differences across tasks show that disambiguating ambiguity in our environment is a highly task specific skill.

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