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On the Temporal Precision of Thought: Individual Differences in the Multisensory Temporal Binding Window Predict Performance on Verbal and Nonverbal Problem Solving Tasks

Leor Zmigrod [1] **and Sharon Zmigrod** [2,*]

[1] Department of Psychology, University of Cambridge, Cambridge, UK

[2] Institute for Psychological Research & Leiden Institute for Brain and Cognition, Leiden University, Leiden, The Netherlands

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Abstract

Although psychology is greatly preoccupied by the tight link between the way that individuals perceive the world and their intelligent, creative behavior, there is little experimental work on the relationship between individual differences in perception and cognitive ability in healthy populations. Here, individual differences in problem solving ability were examined in relation to multisensory perception as measured by tolerance for temporal asynchrony between auditory and visual inputs, i.e., the multisensory temporal binding window. The results demonstrated that enhanced performance in both verbal and nonverbal problem solving tasks (the Remote Associates Test and Raven's Advanced Progressive Matrices Task) is predicted by a narrower audio-visual temporal binding window, which reflects greater sensitivity to subtle discrepancies in sensory inputs. This suggests that the precision of individuals' temporal window of multisensory integration might mirror their capacities for complex reasoning and thus the precision of their thoughts.

Keywords

Multisensory temporal binding window, problem solving, convergent thinking, multisensory integration

1. Introduction

There is a curious yet striking disconnect in the psychological literature between investigations into individual differences in high-level cognitive abili-

[*] To whom correspondence should be addressed. E-mail: szmigrod@fsw.leidenuniv.nl

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ties such as problem solving, creative thinking, and decision-making, and discussions of individual differences in low-level perceptual processes. Although there is a robust understanding that subtle characteristics of one's elementary perception should shape general sophisticated behavior, there is a surprising absence of studies that truly connect the two. In particular, effective integration of multisensory information has been shown to be a critical mechanism for shaping how organisms perceive and interact with a dynamic, noisy, stimuli-rich environment (Bishop and Miller, 2009; Girin *et al.*, 2001; Grant *et al.*, 1998; Stevenson and James, 2009; Sumby and Pollack, 1954; see reviews by: Calvert and Thesen, 2004; King and Calvert, 2001). The advantageous effects of binding multisensory cues on behavior include faster responses (Diederich and Colonius, 2015; Gondan *et al.*, 2005; Hershenson, 1962; Molholm *et al.*, 2002), greater accuracy in localization (Hairston *et al.*, 2003), and higher detection rates (Lovelace *et al.*, 2003). As pointed out by Wallace and Stevenson (2014), since sensory and multisensory mechanisms serve as essential foundations for the formation of perceptual and cognitive representations, the integrity of these multisensory integration systems is likely to affect high-level cognition such as executive function, attention, social cognition, communication, and language (Bahrick, 2010; Bahrick and Lickliter, 2000, 2012, 2014; Stevenson *et al.*, 2014a; Vaillant-Molina and Bahrick, 2012). Indeed, looking at the literature of the psychology of atypical populations, the dysfunctions in high-level cognitive capacities that are often exhibited tend to be accompanied by impairments in multisensory perception. Examples can be found in autism (De Boer-Schellekens *et al.*, 2013; Donohue *et al.*, 2012; Mongillo *et al.*, 2008; Russo *et al.*, 2010; Stevenson *et al.*, 2014b, 2014c, in press; Woynaroski *et al.*, 2013; Zmigrod *et al.*, 2013), dyslexia (Bastien-Toniazzo *et al.*, 2009; Hairston *et al.*, 2005), and schizophrenia (de Gelder *et al.*, 2003, 2005; De Jong *et al.*, 2009; Foucher *et al.*, 2007; Pearl *et al.*, 2009; Ross *et al.*, 2007; Szycik *et al.*, 2009), hinting at links between their atypical multisensory perception and atypical behavioral characteristics (for review see: Wallace and Stevenson, 2014). Although reliable individual differences in the functioning of the multisensory integration system have been documented in healthy populations (Donohue *et al.*, 2010; Stevenson *et al.*, 2012; Stone *et al.*, 2001), the relationship between individual differences in multisensory processing and in higher-order cognition has rarely been empirically explored in typical populations.

Perceiving multisensory stimuli in terms of coherent, unified events is contingent upon the experience of sensory inputs as temporally and spatially synchronous. Temporal simultaneity has been identified as particularly important in order for the brain to discriminate between single and multiple perceptual events (De Gelder and Bertelson, 2003; Sekuler *et al.*, 1997; Vatakis and Spence, 2010; Vroomen and Keetels, 2010). Consequently, multisensory perception is facilitated by the existence of a temporal window that accommodates a limited range of temporal asynchronies between inputs arriving from different modalities (Diederich and Colonius, 2009; Dixon and Spitz, 1980; King, 2005; Spence and Squire, 2003). Studies have demonstrated that simultaneity can still be perceived between bimodal inputs when these are separated by 200 ms (Van Wassenhove *et al.*, 2007), and audio-visual bindings can continue to occur when participants are exposed to temporal asynchrony between auditory and visual stimuli of up to 350 ms (Zmigrod and Hommel, 2011). The size of the temporal window is also dependent on factors such as the duration and intensity of the multisensory inputs (Boenke *et al.*, 2009), the spatial separation of the signals (Zampini *et al.*, 2003, 2005), the sensory pairings being combined (Fujisaki and Nishida, 2009), and the stimulus complexity (Stevenson and Wallace, 2013; Van Eijk *et al.*, 2008; Van Wassenhove *et al.*, 2007; Vatakis and Spence, 2006). Across the lifespan, there is a gradual narrowing of the audio-visual TBW from infancy to adulthood (Hillock *et al.*, 2011; Hillock-Dunn and Wallace, 2012; Lewkowicz, 1996, 2010; Lewkowicz and Flom, 2014) followed by a widening in elderly individuals (Diederich *et al.*, 2008), which might reflect the age-related enhancement and decline in perceptual and cognitive abilities. A wider audio-visual TBW has been documented in atypical populations such as in individuals with autistic spectrum disorders (Bebko *et al.*, 2006; De Boer-Schellekens *et al.*, 2013; Foss-Feig *et al.*, 2010; Kwakye *et al.*, 2011; Stevenson *et al.*, 2014c; however for opposite finding see: Van der Smagt *et al.*, 2007; for a recent review see: Wallace and Stevenson, 2014), suggesting that individual differences in the precision of multisensory perception could reveal important underpinnings in the precision of cognition.

The multisensory temporal binding window (TBW) serves as a filter, such that there is a greater likelihood that information originating from diverse senses are bound together to form a unitary multisensory percept within the TBW, in spite of temporal discrepancies that occur due to inherent differences in physical and neural transmission times of information arriving at different sensory organs (Conrey and Pisoni, 2006; Van Eijk *et al.*, 2008; van Wassenhove *et al.*, 2007; Vroomen and Keetels, 2010). As a filter, the TBW can be thought of as an index of an individual's sensitivity to multisensory asynchrony and indeed Stevenson and colleagues (2012) have shown that individuals with a narrower TBW have an enhanced capacity to distinguish between asynchronous audio-visual inputs, and therefore are less likely to bind asynchronous stimuli and more likely to bind synchronous stimuli into a singular percept, suggesting that the TBW is linked to the accuracy and strength of multisensory integration. Accordingly, video game players exhibit more precise multisensory temporal processing abilities than average (Donohue *et al.*, 2010), highlighting the role of perceptual experience in shaping multisensory discrimination ability. The notion that an altered experience of simultaneity reflects an altered integration of previous and present events and therefore a different structure to conscious experience (Husserl, 1991), as emphasized by Vatakis and Bakou (2015), underscores the relevance of the TBW to all levels of experience beyond multisensory perception itself. Given the variation in the width of the TBW in the healthy population (Donohue *et al.*, 2010; Stevenson *et al.*, 2012; Stone *et al.*, 2001), these findings can be extended further into the question of whether the accuracy of this sensory process is related to accuracy in other realms of cognition.

The present study examines the manner in which high-level problem solving can be understood in terms of its underpinnings in the perceptual system and the way this system binds multisensory information. Problem solving is a particularly interesting facet of cognition not only due to its relevance to daily human activity (Berg *et al.*, 1998; Ohlsson, 2012) but also because of its integrative nature; in the same way that multisensory perception requires the effective amalgamation of multiple inputs to produce a coherent percept, problem solving entails the combination of perceptual and conceptual information in order to generate a correct, appropriate solution. While this is the first study to connect multisensory processing and problem solving, problem solving has been previously related to perception and attention in other paradigms. In the context of diagram-based problem solving, visual attention measured by eye movements has been linked to insightful problem solving (Grant and Spivey, 2003; Knoblich *et al.*, 2001; Thomas and Lleras, 2007) as well as geometric reasoning (Epelboim and Suppes, 1997) and strategies in mental rotation problems (Just and Carpenter, 1985). Furthermore, attentional global-local biases have been demonstrated to predict performance on a divergent thinking task (the Alternate Uses Task), suggesting that flexibility in generating multiple solutions to a given problem might be facilitated by visual-attentional biases to information about the 'bigger picture' at the global level (Zmigrod *et al.*, 2015). Investigations have also recently emerged regarding the relationship between creativity and sensory gating (Zabelina *et al.*, 2015a) and attention (Zabelina and Beeman, 2013; Zabelina *et al.*, 2015b).

In order to assess individual differences in cognitive ability, two measures were used to tap into individuals' capacity to solve complex problems in accurate and adaptive ways. These tests were chosen for their established nature in the literature, and because together they provide a window into both verbal and nonverbal pattern-finding ability. The Raven's Advanced Progressive Matrices (APM; Raven, 1965) is a nonverbal test of novel problem solving, often taken as a measure of general intelligence, problem solving, and reasoning (DeShon *et al.*, 1995; Dillon *et al.*, 1981; Spearman and Wynn-Jones, 1951). In addition, Mednick's (1962) Remote Associates Test (RAT) is a valuable verbal measure of convergent thinking — the process by which individuals generate a single possible solution to a particular problem. The RAT has been consistently used as a form of creative linguistic problem solving (Ansburg and Hill, 2003; Beeman and Bowden, 2000; Bowden and Jung-Beeman, 2003; Dorfman *et al.*, 1996; Schooler and Melcher, 1995). Indeed, RAT performance reliably correlates with successful performance on classic insight problems (Schooler and Melcher, 1995), and performances on the RAT and the APM is positively correlated (Akbari Chermahini and Hommel, 2010; Zmigrod *et al.*, 2015), suggesting that both tasks might tap into similar general cognitive and pattern-finding abilities. Furthermore, in the spirit of multisensory integration, both problem solving tasks require some form of *binding* together of information in order to identify patterns; in Raven's APM, this information is explicitly perceptual, and in the RAT, the information is nonvisual and conceptual.

The overarching research question that guided the present study was whether the brain that deals effectively with the challenges of coherent multisensory perception by accurately detecting asynchrony of inputs is also a brain that detects perceptual and conceptual patterns. A narrower TBW, measured *via* enhanced detection of asynchrony between auditory and visual features, would imply lower tolerance for subtle sensory discrepancies and thus enhanced temporal precision of perception. Given the tight links between sensory, attentional, and cognitive processes, it is hypothesized that greater perceptual precision (a narrower TBW) might be related to enhanced ability to complete patterns. A narrower temporal binding window implies that the individual is more accurate at identifying relevance and irrelevance, i.e., detecting sensory inputs that are relevant (synchronous) or irrelevant (asynchronous) to the event. Therefore, it might be that ability to detect such relevance and irrelevance at the multisensory perceptual level is correlated with a capacity to ascertain which pieces of information are relevant or irrelevant to the pattern problems of the Raven's APM and RAT.

2. Materials and Methods

2.1. Participants

In total, 124 native Dutch Leiden University students (60 men; mean age = 20 years; SD = 2.3; age range: 17–28 years) took part in the study for course credits or a financial reward. Six participants were excluded from the analysis due to deviation of more than 2 SD from the mean in their performances. All participants were right-handed with normal or corrected-to-normal vision. Exclusion criteria included: a history of psychiatric disorders, drug abuse, and active medication. Participants gave their written informed consent to participate in the study.

2.2. Stimuli and Procedure

2.2.1. Simultaneity Judgment Task

The audio-visual simultaneity judgment task was based on a design by Zmigrod and Hommel (2011), where participants perform a two-alternative forced-choice task in which they indicate whether they perceived the presented auditory and visual features as occurring simultaneously or as two separate events. The bimodal stimuli were composed of pure tones with 1000 Hz or 3000 Hz (duration 50 ms) presented at approximately 70 dB SPL, and accompanied by a colored circle which was presented randomly with the following colors: red, blue, green, brown, yellow, black, purple, or pink. The sound preceded the color at the stimulus onset asynchronies (SOAs) of 150, 250, or 350 ms. The SOAs were used as the independent variable in relation to subjects' judgment of simultaneity between the sound and color. The order of the trials was randomized. The participants were instructed to judge whether the sound and color appeared 'at the same time (together)' and then press 'Z' (corresponding to the Dutch word 'same'; 'zelfde') or 'not at the same time (separately)' and press on the 'N' key (for the Dutch word 'not the same'; 'niet hetzelfde'). The task consisted of 144 trials and lasted a total of 15 min. The use of two tones and eight colors creates 16 possible combinations presented randomly to the participant, thus preventing habituation to the stimuli.

2.2.2. Raven's Advanced Progressive Matrices Task (Raven's APM)

The Raven's Advanced Progressive Matrices task (APM; Raven, 1965) was used to assess nonverbal novel problem solving ability. This task is often used to estimate fluid intelligence and Spearman's g. Participants are provided with a series of pictorial designs with a missing element that completes the pattern, and are requested to select the correct element out of a number of six possible answers. In this task, we used 30 items that progressively increased in difficulty over the 20 min during which the APM was administered.

2.2.3. Remote Associates Task (RAT)

In order to assess verbal problem solving and convergent thinking, a computerized Dutch version of the Remote Associates Task (RAT) was adapted from Akbari Chermahini and colleagues (2012), and comprised of 30 problems (Cronbach's alpha = 0.85). In the RAT, each item entails three words (such as: *boot*, *summer*, *ground*), all of which may be related to a fourth word *via* the formation of compound words or the identification of a semantic associate (*camp*). The participants are asked to provide an answer for any given item within 30 s.

2.3. Procedure

The participants read and signed the informed consent form before the beginning of the experiment. All the participants completed the simultaneity judgment task, the RAT, and the Raven's APM task. The order of the tasks was counterbalanced between participants. The study conformed to the ethical standards of the Declaration of Helsinki and was approved by the Ethical Committee of Leiden University.

2.4. Data Analysis

In order to analyze audiovisual synchrony perception and the temporal binding window, two methods were used. Firstly, simultaneity judgment was calculated as the percentage of responses whereby subjects indicated the stimuli occurred at 'the same time' for each of the SOAs (150, 250, 350 ms). And secondly, responses from the simultaneity judgment task were used to compute the width of the audio-visual TBW for each participant, in accordance with methods typically used in the field (Hillock *et al.*, 2011; Hillock-Dunn and Wallace, 2012; Powers *et al.*, 2009; Schall and Hanes, 1993; Stevenson *et al.*, 2011). In order to do this, the percentage of synchrony judgment was calculated for each SOA per participant, and a psychometric sigmoid function was fitted to these rates of perceived simultaneity in MATLAB. Since the three SOAs that were investigated in the present study did not include SOA = 0 ms, it was assumed that at SOA = 0 ms the participant's rate of perceived synchrony would be 100% (meaning that the individual would not report asynchrony when the auditory and visual features were presented with exact simultaneity). In addition, in order to ensure that the sigmoid curve was representative of the auditory-leading TBW, it was also assumed that at SOA = 600 ms the probability of simultaneity report equaled 0%. This is based on previous literature indicating that beyond SOAs of 500 ms, perceived synchrony in healthy adults is effectively zero (e.g., Hillock-Dunn and Wallace, 2012; Massaro *et al.*, 1996). In order to derive a TBW score, each subject's audio-visual TBW was estimated at the SOA where the y-value of the best-fit sigmoid was equal to a 50% rate of synchrony perception. A statistical criterion level of 50% was chosen based on prior research (as used in Stevenson and Wallace (2013), Stevenson and colleagues (2011, 2012)).

3. Results

3.1. Simultaneity Judgment and Temporal Binding Window Effects

The audio-visual temporal binding window was analyzed in two ways; first, computing the average rate of simultaneity judgment per SOA, and second, deriving a unitary TBW score by fitting the data to a sigmoid function and calculating the width of each participant's audio-visual TBW at the point where the function estimates their synchrony perception to be equal to 50%. Descriptive statistics regarding average simultaneity judgment and the calculated

Table 1.
Descriptive statistics of the average synchrony judgment at each SOA, and the computed TBW score

	Mean (SD)
Synchrony judgment	
SOA = 150 ms	80.4% (14.2)
SOA = 250 ms	42.9% (19.1)
SOA = 350 ms	15.5% (11.9)
TBW score	229.73 ms (44.97)

Notes. $N = 118$. SOA = stimuli onset asynchrony.

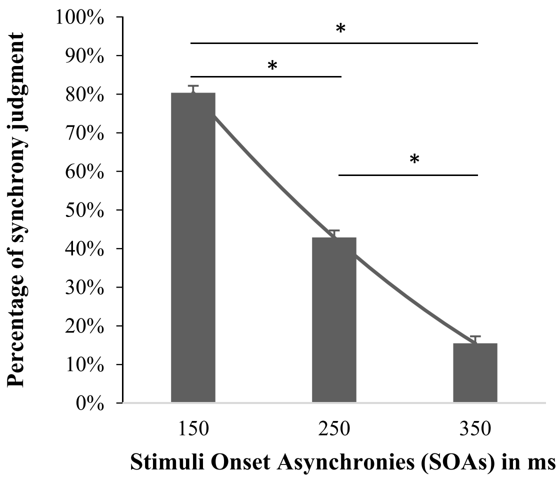

Figure 1. Percentage of synchrony judgment with error bars as a function of stimuli onset asynchronies (SOAs). $^{*}p < 0.001$.

TBW score are provided in Table 1. As depicted in Fig. 1, people report subjective synchrony perception of the auditory and visual features despite the fact that all the stimuli had a stimulus onset asynchrony (SOAs) of either 150, 250 or 350 ms, suggesting the existence of a temporal binding window (TBW) in multisensory perception, replicating previous findings (e.g., Van Wassenhove *et al.*, 2007; Zmigrod and Hommel, 2011). This subjective perception of synchrony was reduced as the SOA between the features increased, as can be observed from the main effect of SOA in repeated measures ANOVA (Fig. 1), $F(2, 234) = 935.065$, $p < 0.0001$, $\eta_p^2 = 0.889$. Post-hoc Bonferroni confirmed significant differences between all the SOAs, all $p < 0.0001$.

3.2. Complex Problem Solving Performances

The RAT and Raven's APM scores were measured in terms of the number of correct items. Furthermore, replicating previous findings (Akbari Chermahini and Hommel, 2010; Zmigrod *et al.*, 2015), there was a positive correlation between the performances in the RAT and the performances in Raven's APM, $r = 0.223$, $p < 0.05$.

3.3. Relationship Between Synchrony Judgment and Problem Solving

Table 2 shows the correlations between performance on the two problem solving tasks and synchrony judgment. RAT scores were significantly negatively correlated with SOAs of 150, 250, and 350 ms as well as with the computed TBW score. In addition, Raven's APM scores were negatively correlated with SOAs of 250 and 350 ms, and with the TBW score.

In order to evaluate whether the synchrony judgment of multisensory stimuli with different SOAs between the auditory and the visual features can predict problem solving performances in verbal (RAT) and nonverbal (Raven's APM) tasks, two multiple linear regression analyses were conducted. So as to ensure that age and gender did not contribute to the individual differences predicting the RAT and the Raven's APM scores, a two-stage liner regression was performed with age and gender in the first step and synchrony judgments in the second step (Table 3).

The hierarchical linear regression analyses revealed that synchrony judgment at SOA of 350 ms can significantly predict the participants' performance on the RAT and the Raven's APM task (Table 3). Age and gender did not significantly contribute to the prediction. As is evident from Fig. 2, the higher the synchrony judgment at SOA 350 ms (reflecting a wider temporal binding window), the poorer the performances on the verbal and nonverbal problem solving tasks. These findings show a link between low-level perceptual processes and high-level cognitive functions.

Table 2.
Correlations between age, gender, synchrony judgment for SOAs 150, 250, 350 ms and performance in problem solving in verbal (RAT) and nonverbal (Raven's APM) tasks

	Stimuli onset asynchronies (SOAs)			Derived TBW score
	150 ms	250 ms	350 ms	
RAT scores	−0.191*	−0.165*	−0.238**	−0.226*
Raven's APM scores	−0.031	−0.253**	−0.354**	−0.258**

Notes. $N = 118$. * $p < 0.05$; ** $p < 0.005$.

Table 3.
Results of multiple linear regression analyses for RAT scores and Raven's APM scores as the dependent variables with age and gender as first step of the linear regression and synchrony judgment (SOAs: 150, 250, 350) as the second step of the linear regression

	RAT scores			Raven's APM scores		
	B (SE *B*)	β	*t*	*B* (SE *B*)	β	*t*
Step 1						
Age	0.025 (0.15)	0.170	1.679	−0.028 (0.12)	−0.023	−0.225
Gender	−0.44 (0.69)	−0.065	−0.641	−0.43 (0.56)	−0.078	−0.760
Step 2						
Age	0.26 (0.15)	0.174	1.768	0.003 (0.12)	0.003	0.029
Gender	−0.13 (0.68)	−0.019	−0.190	−0.058 (0.54)	−0.011	−0.107
Synchrony judgment						
SOA: 150 ms	−4.66 (2.47)	−0.193	−1.884	0.61 (1.97)	0.031	0.308
SOA: 250 ms	2.91 (2.59)	0.0162	1.121	−0.29 (2.06)	−0.021	−0.143
SOA: 350 ms	−9.17 (3.77)	−0.319	−2.432*	−7.85 (3.00)	−0.342	−2.62**
	Step 1: $R^2 = 0.043$, $F(2, 115) = 2.57$, NS; Step 2: $R^2 = 0.123$, $F(5, 112) = 3.15$, $p < 0.01$			Step 1: $R^2 = 0.005$, $F(2, 115) = 0.296$, NS; Step 2: $R^2 = 0.126$, $F(5, 112) = 3.23$, $p < 0.01$		

Notes. $N = 118$. $^*p < 0.05$; $^{**}p < 0.01$.

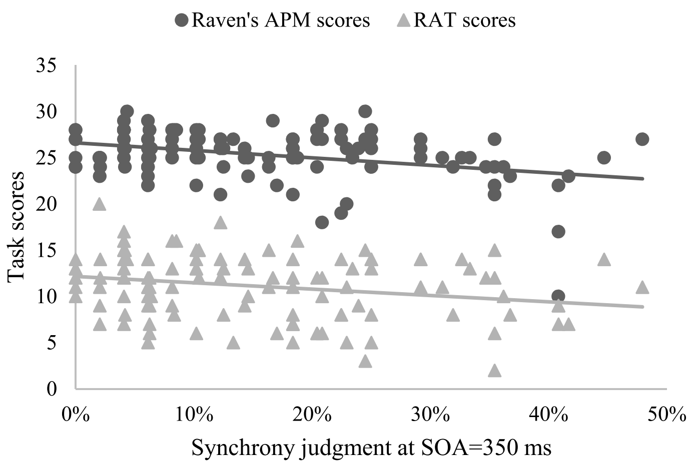

Figure 2. Scatter plot depicting the correlations between the synchrony judgment at SOA of 350 ms and the scores from both the verbal problem solving task (RAT) and the nonverbal problem solving task (Raven's APM).

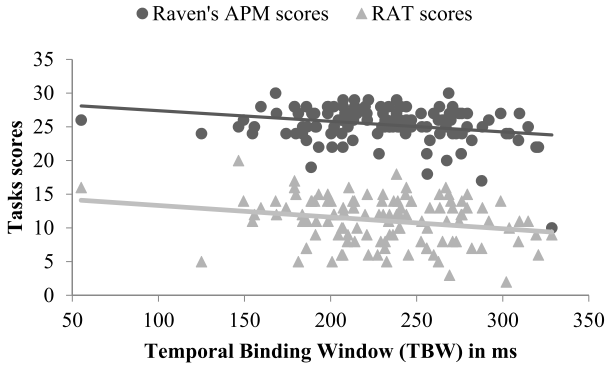

Figure 3. Scatter plot depicting the correlations between the TBW in milliseconds and the scores from both the verbal problem solving task (RAT) and the nonverbal problem solving task (Raven's APM).

Table 4.
Results of multiple linear regression analyses for RAT scores and Raven's APM scores as the dependent variables with age and gender as first step of the linear regression and TBW as the second step of the linear regression

	RAT scores			Raven's APM scores		
	B (SE *B*)	*β*	*t*	*B* (SE *B*)	*β*	*t*
Step 1						
Age	0.25 (0.15)	0.170	1.68	−0.028 (0.12)	−0.023	−0.225
Gender	−0.44 (0.69)	−0.065	−0.065	−0.43 (0.56)	−0.078	−0.760
Step 2						
Age	0.24 (0.15)	0.162	1.768	−0.040 (0.12)	−0.034	0.336
Gender	−0.24 (0.69)	−0.035	−1.90	−0.222 (0.55)	−0.041	−0.402
TBW	−0.016 (0.007)	−0.203	−2.231*	−0.016 (0.006)	−0.255	−2.780**
	Step 1: $R^2 = 0.043$, $F(2, 115) = 2.57$, NS; Step 2: $R^2 = 0.083$, $F(3, 114) = 3.431$, $p < 0.05$			Step 1: $R^2 = 0.005$, $F(2, 115) = 0.296$, NS; Step 2: $R^2 = 0.068$, $F(3, 114) = 2.785$, $p < 0.05$		

Notes. $N = 118$. $^{*}p < 0.05$; $^{**}p < 0.01$.

In addition, this pattern of results was also evident when examining the relationship between the TBW score and the problem solving tasks (see Fig. 3). Two-stage linear regression analyses were conducted with age and gender in the first step and TBW score in the second step, demonstrating that a smaller TBW score is predictive of performance on the RAT and Raven's APM (Table 4).

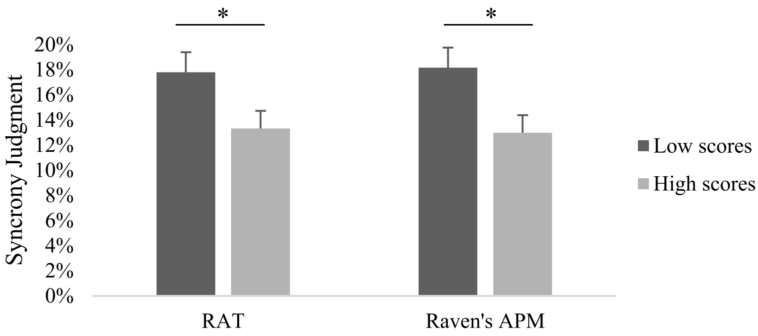

Figure 4. Percentage of synchrony judgment at SOA = 350 ms (with error bars) as a function of high scores and low scores for verbal (RAT) and nonverbal (Raven's APM) complex problems. $^{*}p < 0.05$.

In order to further investigate these relationships, the participants were split along the performances median into 'high performers' and 'low performers' for both the RAT and Raven's APM. As is demonstrated in Fig. 4, t-test analyses revealed significant differences between the groups in synchrony judgment at SOA 350 ms, both in the verbal task (RAT): $t(116) = 2.06$, $p < 0.05$, and in the nonverbal task (Raven's APM): $t(116) = 2.40$, $p < 0.05$.

3.4. Gender Effect

Interestingly, in terms of gender differences, there was a significant difference in the simultaneity judgment of SOA 250 ms between males ($N = 59$) and females ($N = 59$), $F(1, 116) = 4.104$, $p < 0.05$, and close to significant in SOA 350 ms, $F(1, 116) = 3.211$, $p = 0.076$, as is depicted in Fig. 5. Additionally, the difference in the calculated TBW score between males ($M = 222.29$, SD $= 48.5$) and females ($M = 237.16$, SD $= 40.2$) was close to statistical significance, $F(1, 116) = 3.289$, $p = 0.072$. This suggests that a narrower TBW might be present in males compared to females (Fig. 5). Note that there was no gender difference in the performance of the problem solving tasks, $p > 0.1$.

4. Discussion

The present study is the first to examine the relationship between multisensory integration and problem solving in the healthy population. The study demonstrated the presence of a temporal binding window (TBW) in multisensory perception, replicating previous work (Conrey and Pisoni, 2006; Diederich and Colonius, 2015; Dixon and Spitz, 1980; Spence and Squire, 2003; Van Wassenhove et al., 2007; Zmigrod and Hommel, 2011; for review: Vroomen and Keetels, 2010), as well as individual differences in multisensory simultaneity judgment, implying the existence of variation in the extent to which

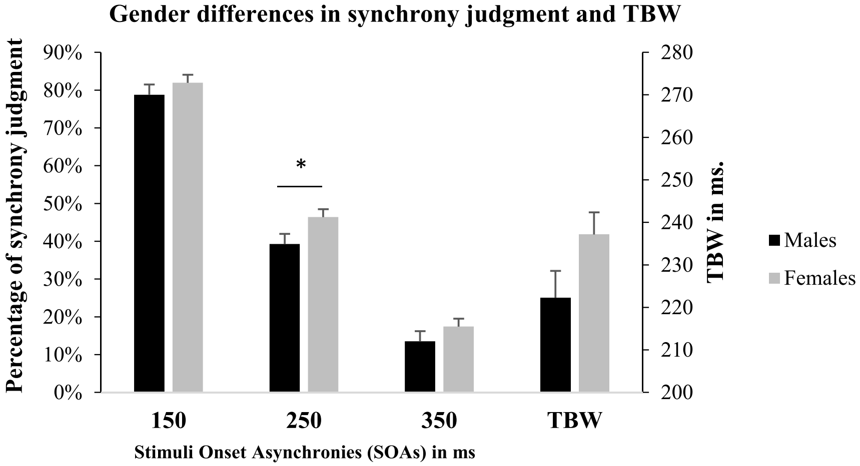

Figure 5. Percentage of synchrony judgment as a function of stimulus onset asynchronies (SOAs) and calculated temporal binding window (TBW) of males and females with error bars. $^*p < 0.05$.

individuals are sensitive to asynchrony between inputs originating from different sensory modalities (Donohue *et al.*, 2010; Stevenson *et al.*, 2012; Stone *et al.*, 2001). This was illustrated through simultaneity judgment scores as well as *via* the computation of a TBW score, in accordance with previous work in the field (Hillock *et al.*, 2011; Hillock-Dunn and Wallace, 2012; Powers *et al.*, 2009; Schall and Hanes, 1993; Stevenson *et al.*, 2011, 2012, 2013). Moreover, an interesting finding emerging from the data is a gender difference in simultaneity judgment, whereby males tend to exhibit a narrower TBW than females (Fig. 5). This intriguing pattern requires further empirical exploration. With regards to the administered problem solving tasks, there was a correlation between performance on the Raven's APM and the RAT, replicating previous findings (Akbari Chermahini and Hommel, 2010; Zmigrod *et al.*, 2015). Notably, there was no gender difference in performance on the Raven's APM or the RAT. Most interestingly for the aims of this study, significant correlations were found between audio-visual simultaneity judgment and performance on the problem solving tasks, as well as between the derived TBW score and problem solving ability; the results demonstrate that better performance in verbal and nonverbal problem solving tasks is related to and may be predicted by a narrower multisensory temporal binding window (Figs 2, 3 and 4). A narrower TBW indicates greater sensitivity to stimulus onset asynchrony between auditory and visual features, and reflects increased accuracy and strength of multisensory integration (Stevenson *et al.*, 2012). Thus, individuals who displayed greater sensitivity and precision in detecting audio-visual asynchrony were also more likely to perform well on tasks requiring detection of complex patterns.

It is striking that performance on both the verbal and nonverbal tasks was related to the width of the audio-visual TBW, especially given that neither task is multisensory in nature. Interestingly, the pattern of the relationship between audio-visual temporal integration and task performance was similar for both the verbal and nonverbal tasks, as evident in Figs 2 and 3. Additionally, while the simultaneity judgment task is one that taps into perception of the temporal structure of audiovisual stimuli (Stevenson and Wallace, 2013; Van Eijk *et al.*, 2008; Vroomen and Keetels, 2010), the problem solving tasks did not involve any temporally sequential presentation of information. This might suggest that the link between multisensory perception and complex cognition does not merely lie in the direct reliance of cognitive processes on sensory input — there might be some core precision or sensitivity that is present at multiple perceptual levels and timescales and which also facilitates accurate and sophisticated higher-level behavior. It is also interesting to note that whereas the items of the Raven's APM offer the correct solution in a visible format to the participant, and so entail problem solving *via selection* of the answer, the RAT involves *generation* of an idea from related but indirect cues. Therefore, the finding that performance on both of these measures is predicted by audio-visual simultaneity judgment might demonstrate that this perceptual precision is related to multiple facets of the problem solving process. Moreover, it is vital to consider that while problem solving is generally considered to be, at least in part, a conscious, deliberative, resource-intensive activity (Dorfman *et al.*, 1996), the detection of multisensory simultaneity reflects a more sub-conscious, automatic processing and integration of inputs (Shams, 2002; Zmigrod and Hommel, 2011). In conjunction with the present results, one could postulate that there may be a domain-general trait-level sharpness, which permeates perceptual and cognitive processes across multiple levels of awareness.

Previous research has demonstrated that the multisensory TBW has a dynamic, flexible nature both between and within individuals. In infants and adults, the audiovisual temporal binding window can extend and recalibrate in relation to the temporal statistics of the environment (Fujisaki *et al.*, 2004; Keetels and Vroomen, 2007, 2008; Lewkowicz, 2010; Navarra *et al.*, 2005; Vroomen *et al.*, 2004), and perceptual training has been shown to reduce the width of the TBW (Powers *et al.*, 2009, 2012; Stevenson *et al.*, 2013). Furthermore, specific task demands can influence the malleability of the boundaries of individuals' TBW (Mégevand *et al.*, 2013), signifying that adaptive recalibration of the width of the TBW can take place in order to optimize performance (Diederich and Colonius, 2015). Additionally, work using noninvasive brain stimulation techniques has revealed that anodal transcranial direct current stimulation (tDCS) over the right posterior parietal cortex can significantly shrink the audiovisual temporal binding window (Zmigrod and Zmigrod, 2015).

In conjunction with these demonstrations of how the width of the TBW can be modified temporarily, the present findings might possess clinical implications for populations such as autistic or elderly individuals, who tend to experience an abnormally wide temporal binding window (Foss-Feig *et al.*, 2010; Hillock *et al.*, 2011; Kwakye *et al.*, 2011). In particular, autism spectrum disorders (ASD) have been linked to atypical sensory processing (Cascio *et al.*, 2012; Foss-Feig *et al.*, 2012; Kujala *et al.*, 2013; Visser *et al.*, 2013), and recent work is indicating the presence of deficits in binding of sensory information across modalities (Stevenson *et al.*, 2014b), as evident in audiovisual processing (Bebko *et al.*, 2014; De Gelder *et al.*, 1991; Irwin *et al.*, 2011; Mongillo *et al.*, 2008), audiotactile processing (Russo et al., 2010), visuohaptic processing (Cascio et al., 2012), and stimulus–response binding (Zmigrod *et al.*, 2013). Given the findings of the present study — that multisensory function is associated with performance on higher cognitive domains — it will therefore be interesting to explore whether using perceptual training (Powers *et al.*, 2009) or brain stimulation techniques (Zmigrod and Zmigrod, 2015) to narrow the TBW will have positive effects on behavioral outcomes that transcend multisensory processing. This is especially relevant to populations with a wider TBW, as studies have demonstrated that the greatest benefit from perceptual training aimed at narrowing the width of the TBW is experienced by those with the widest initial TBW (Powers *et al.*, 2009; Stevenson *et al.*, 2013). Future studies that experimentally manipulate the TBW should examine whether there are associated alterations in higher-order cognitive capacities such as problem solving, pattern finding, and reasoning.

By demonstrating that individual differences in multisensory integration can predict performance on verbal and nonverbal problem solving tasks, the present study emphasizes the tight link between the unique, subtle way that individuals perceive the world and their intelligent, creative behavior. Since the precision with which multisensory information is integrated serves to amplify the salience of biologically meaningful events (Stein and Stanford, 2008), lower tolerance for asynchrony allows for perceptual acuity that is then translated into behavioral acuity. Future research should be directed at further investigating the links between low-level perceptual processing abilities and how these might relate to higher-level cognitive abilities such as reasoning, decision making, and creativity. Multisensory paradigms such as temporal order judgment (Spence *et al.*, 2003; Vatakis *et al.*, 2008; Vroomen *et al.*, 2004; Zampini *et al.*, 2003) and perceptual illusions such as the McGurk effect (e.g., Bebko *et al.*, 2014; Irwin *et al.*, 2011) might be worthwhile to explore in this context, as well as other forms of higher cognition such as decision making and social cognition. The present study can also be extended by investigating a wider range of SOAs, such that the point of subjective simultaneity can be derived (e.g., as in Fujisaki *et al.*, 2004; Noel *et al.*, 2015). An individual differences perspective is particularly valuable, not only because it helps to understand the general and idiosyncratic relations between low-level perception and high-level cognition, but also because it emphasizes that the differences between typical and atypical populations in terms of perceptual and behavioral tendencies are likely to lie along continua rather than dichotomies. When the Irish poet W. B. Yeats claimed that "*the world is full of magical things, patiently waiting for our senses to grow sharper*", the Nobel laureate may not have imagined that indeed the temporal sharpness of how our senses integrate information is related to our capacity to solve and unravel puzzles. It thus appears that the precision of individuals' temporal window of multisensory integration might mirror the precision of their thoughts.

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References

Akbari Chermahini, S. and Hommel, B. (2010). The (b) link between creativity and dopamine: spontaneous eye blink rates predict and dissociate divergent and convergent thinking, *Cognition* **115**, 458–465.

Akbari Chermahini, S. A., Hickendorff, M. and Hommel, B. (2012). Development and validity of a Dutch version of the remote associates task: an item-response theory approach, *Think. Skills Creat.* **7**, 177–186.

Ansburg, P. I. and Hill, K. (2003). Creative and analytic thinkers differ in their use of attentional resources, *Pers. Indiv. Dif.* **34**, 1141–1152.

Bahrick, L. E. (2010). Intermodal perception and selective attention to intersensory redundancy: implications for typical social development and autism, in: *Blackwell Handbook of Infant Development*, 2nd edn., G. Bremner and T. D. Wachs (Eds), pp. 120–166. Blackwell Publishing, Oxford, UK.

Bahrick, L. E. and Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy, *Dev. Psychol.* **36**, 190–201.

Bahrick, L. E. and Lickliter, R. (2012). The role of intersensory redundancy in early perceptual, cognitive, and social development, in: *Multisensory Development*, A. J. Bremner, D. J. Lewkowicz and C. Spence (Eds), pp. 183–206. Oxford University Press, Oxford, UK.

Bahrick, L. E. and Lickliter, R. (2014). Learning to attend selectively the dual role of intersensory redundancy, *Curr. Dir. Psychol. Sci.* **23**, 414–420.

Bastien-Toniazzo, M., Stroumza, A. and Cavé, C. (2009). Audio-visual perception and integration in developmental dyslexia: an exploratory study using the McGurk effect, *Curr. Psychol. Lett.* **25**, 2–14.

Bebko, J. M., Weiss, J. A., Demark, J. L. and Gomez, P. (2006). Discrimination of temporal synchrony in intermodal events by children with autism and children with developmental disabilities without autism, *J. Child Psychol. Psychiatry* **47**, 88–98.

Bebko, J. M., Schroeder, J. H. and Weiss, J. A. (2014). The McGurk effect in children with autism and Asperger syndrome, *Autism Res.* **7**, 50–59.

Beeman, M. J. and Bowden, E. M. (2000). The right hemisphere maintains solution-related activation for yet-to-be-solved problems, *Mem. Cogn.* **28**, 1231–1241.

Berg, C. A., Strough, J., Calderone, K. S., Sansone, C. and Weir, C. (1998). The role of problem definitions in understanding age and context effects on strategies for solving everyday problems, *Psychol. Aging* **13**, 29–44.

Bishop, C. W. and Miller, L. M. (2009). A multisensory cortical network for understanding speech in noise, *J. Cogn. Neurosci.* **21**, 1790–1804.

Boenke, L. T., Deliano, M. and Ohl, F. W. (2009). Stimulus duration influences perceived simultaneity in audiovisual temporal-order judgment, *Exp. Brain Res.* **198**, 233–244.

Bowden, E. M. and Jung-Beeman, M. (2003). Normative data for 144 compound remote associate problems, *Behav. Res. Methods Instrum. Comput.* **35**, 634–639.

Calvert, G. A. and Thesen, T. (2004). Multisensory integration: methodological approaches and emerging principles in the human brain, *J. Physiol. Paris* **98**, 191–205.

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L. and Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception, *Autism* **16**, 406–419.

Conrey, B. and Pisoni, D. B. (2006). Auditory–visual speech perception and synchrony detection for speech and nonspeech signals, *J. Acoust. Soc. Am.* **119**, 4065–4073.

De Boer-Schellekens, L., Eussen, M. and Vroomen, J. (2013). Diminished sensitivity of audiovisual temporal order in autism spectrum disorder, *Front. Integr. Neurosci.* **7**, 8. DOI:10.3389/fnint.2013.00008.

De Gelder, B. and Bertelson, P. (2003). Multisensory integration, perception and ecological validity, *Trends Cogn. Sci.* **7**, 460–467.

De Gelder, B., Vroomen, J. and Van der Heide, L. (1991). Face recognition and lip-reading in autism, *Eur. J. Cogn. Psychol.* **3**, 69–86.

De Gelder, B., Vroomen, J., Annen, L., Masthof, E. and Hodiamont, P. (2003). Audio-visual integration in schizophrenia, *Schizophr. Res.* **59**, 211–218.

De Gelder, B., Vroomen, J., De Jong, S. J., Masthoff, E. D., Trompenaars, F. J. and Hodiamont, P. (2005). Multisensory integration of emotional faces and voices in schizophrenics, *Schizophr. Res.* **72**, 195–203.

De Jong, J. J., Hodiamont, P. P. G., Van den Stock, J. and De Gelder, B. (2009). Audiovisual emotion recognition in schizophrenia: reduced integration of facial and vocal affect, *Schizophr. Res.* **107**, 286–293.

DeShon, R. P., Chan, D. and Weissbein, D. A. (1995). Verbal overshadowing effects on raven's advanced progressive matrices: evidence for multidimensional performance determinants, *Intelligence* **21**, 135–155.

Diederich, A. and Colonius, H. (2009). Crossmodal interaction in speeded responses: time window of integration model, *Progr. Brain Res.* **174**, 119–135.

Diederich, A. and Colonius, H. (2015). The time window of multisensory integration: relating reaction times and judgments of temporal order, *Psychol. Rev.* **122**, 232–241.

Diederich, A., Colonius, H. and Schomburg, A. (2008). Assessing age-related multisensory enhancement with the time-window-of-integration model, *Neuropsychologia* **46**, 2556–2562.

Dillon, R. F., Pohlmann, J. T. and Lohman, D. F. (1981). A factor analysis of Raven's advanced progressive matrices freed of difficulty factors, *Educ. Psychol. Meas.* **41**, 1295–1302.

Dixon, N. F. and Spitz, L. (1980). The detection of auditory visual desynchrony, *Perception* **9**, 719–721.

Donohue, S. E., Woldorff, M. G. and Mitroff, S. R. (2010). Video game players show more precise multisensory temporal processing abilities, *Atten. Percept. Psychophys.* **72**, 1120–1129.

Donohue, S. E., Darling, E. F. and Mitroff, S. R. (2012). Links between multisensory processing and autism, *Exp. Brain Res.* **222**, 377–387.

Dorfman, J., Shames, V. A. and Kihlstrom, J. F. (1996). Intuition, incubation, and insight: implicit cognition in problem solving, in: *Implicit Cognition*, G. Underwood (Ed.), pp. 257–296. Oxford University Press, Oxford, UK.

Epelboim, J. and Suppes, P. (1997). Eye movements during geometrical problem solving, *Perception* **26**(1 Suppl.), 138.

Foss-Feig, J. H., Kwakye, L. D., Cascio, C. J., Burnette, C. P., Kadivar, H., Stone, W. L. and Wallace, M. T. (2010). An extended multisensory temporal binding window in autism spectrum disorders, *Exp. Brain Res.* **203**, 381–389.

Foss-Feig, J. H., Heacock, J. L. and Cascio, C. J. (2012). Tactile responsiveness patterns and their association with core features in autism spectrum disorders, *Res. Autism Spectr. Disord.* **6**, 337–344.

Foucher, J. R., Lacambre, M., Pham, B. T., Giersch, A. and Elliott, M. A. (2007). Low time resolution in schizophrenia: lengthened windows of simultaneity for visual, auditory and bimodal stimuli, *Schizophr. Res.* **97**, 118–127.

Fujisaki, W. and Nishida, S. Y. (2009). Audio-tactile superiority over visuo-tactile and audio-visual combinations in the temporal resolution of synchrony perception, *Exp. Brain Res.* **198**, 245–259.

Fujisaki, W., Shimojo, S., Kashino, M. and Nishida, S. Y. (2004). Recalibration of audiovisual simultaneity, *Nat. Neurosci.* **7**, 773–778.

Girin, L., Schwartz, J. L. and Feng, G. (2001). Audio-visual enhancement of speech in noise, *J. Acoust. Soc. Am.* **109**, 3007–3020.

Gondan, M., Niederhaus, B., Rösler, F. and Röder, B. (2005). Multisensory processing in the redundant-target effect: a behavioral and event-related potential study, *Percept. Psychophys.* **67**, 713–726.

Grant, E. R. and Spivey, M. J. (2003). Eye movements and problem solving guiding attention guides thought, *Psychol. Sci.* **14**, 462–466.

Grant, K. W., Walden, B. E. and Seitz, P. F. (1998). Auditory–visual speech recognition by hearing-impaired subjects: consonant recognition, sentence recognition, and auditory–visual integration, *J. Acoust. Soc. Am.* **103**, 2677–2690.

Hairston, W. D., Laurienti, P. J., Mishra, G., Burdette, J. H. and Wallace, M. T. (2003). Multisensory enhancement of localization under conditions of induced myopia, *Exp. Brain Res.* **152**, 404–408.

Hairston, W. D., Burdette, J. H., Flowers, D. L., Wood, F. B. and Wallace, M. T. (2005). Altered temporal profile of visual–auditory multisensory interactions in dyslexia, *Exp. Brain Res.* **166**, 474–480.

Hershenson, M. (1962). Reaction time as a measure of intersensory facilitation, *J. Exp. Psychol.* **63**, 289–293.

Hillock, A. R., Powers, A. R. and Wallace, M. T. (2011). Binding of sights and sounds: age-related changes in multisensory temporal processing, *Neuropsychologia* **49**, 461–467.

Hillock-Dunn, A. and Wallace, M. T. (2012). Developmental changes in the multisensory temporal binding window persist into adolescence, *Dev. Sci.* **15**, 688–696.

Husserl, E. (1991). *On the Phenomenology of the Consciousness of Internal Time (1893–1917)*, Vol. 4. Springer Science & Business Media, Dordrecht, The Netherlands.

Irwin, J. R., Tornatore, L. A., Brancazio, L. and Whalen, D. H. (2011). Can children with autism spectrum disorders "hear" a speaking face? *Child Dev.* **82**, 1397–1403.

Just, M. A. and Carpenter, P. A. (1985). Cognitive coordinate systems: accounts of mental rotation and individual differences in spatial ability, *Psychol. Rev.* **92**, 137–172.

Keetels, M. and Vroomen, J. (2007). No effect of auditory–visual spatial disparity on temporal recalibration, *Exp. Brain Res.* **182**, 559–565.

Keetels, M. and Vroomen, J. (2008). Temporal recalibration to tactile–visual asynchronous stimuli, *Neurosci. Lett.* **430**, 130–134.

King, A. J. (2005). Multisensory integration: strategies for synchronization, *Curr. Biol.* **15**, R339–R341.

King, A. J. and Calvert, G. A. (2001). Multisensory integration: perceptual grouping by eye and ear, *Curr. Biol.* **11**, R322–R325.

Knoblich, G., Ohlsson, S. and Raney, G. E. (2001). An eye movement study of insight problem solving, *Mem. Cogn.* **29**, 1000–1009.

Kujala, T., Lepistö, T. and Näätänen, R. (2013). The neural basis of aberrant speech and audition in autism spectrum disorders, *Neurosci. Biobehav. Rev.* **37**, 697–704.

Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L. and Wallace, M. T. (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders, *Front. Integr. Neurosci.* **4**, 129. DOI:10.3389/fnint.2010.00129.

Lewkowicz, D. J. (1996). Perception of auditory–visual temporal synchrony in human infants, *J. Exp. Psychol. Hum. Percept. Perform.* **22**, 1094–1106.

Lewkowicz, D. J. (2010). Infant perception of audio-visual speech synchrony, *Dev. Psychol.* **46**, 66–77.

Lewkowicz, D. J. and Flom, R. (2014). The audiovisual temporal binding window narrows in early childhood, *Child Dev.* **85**, 685–694.

Lovelace, C. T., Stein, B. E. and Wallace, M. T. (2003). An irrelevant light enhances auditory detection in humans: a psychophysical analysis of multisensory integration in stimulus detection, *Cognitive Brain Tesearch* **17**, 447–453.

Massaro, D. W., Cohen, M. M. and Smeele, P. M. (1996). Perception of asynchronous and conflicting visual and auditory speech, *J. Acoust. Soc. Am.* **100**, 1777–1786.

Mednick, S. (1962). The associative basis of the creative process, *Psychol. Rev.* **69**, 220–232.

Mégevand, P., Molholm, S., Nayak, A. and Foxe, J. J. (2013). Recalibration of the multisensory temporal window of integration results from changing task demands, *PLoS ONE* **8**, e71608. DOI:10.1371/journal.pone.0071608.

Molholm, S., Ritter, W., Murray, M. M., Javitt, D. C., Schroeder, C. E. and Foxe, J. J. (2002). Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study, *Cogn. Brain Res.* **14**, 115–128.

Mongillo, E. A., Irwin, J. R., Whalen, D. H., Klaiman, C., Carter, A. S. and Schultz, R. T. (2008). Audiovisual processing in children with and without autism spectrum disorders, *J. Autism Dev. Disord.* **38**, 1349–1358.

Navarra, J., Vatakis, A., Zampini, M., Soto-Faraco, S., Humphreys, W. and Spence, C. (2005). Exposure to asynchronous audiovisual speech extends the temporal window for audiovisual integration, *Cogn. Brain Res.* **25**, 499–507.

Noel, J. P., Wallace, M. T., Orchard-Mills, E., Alais, D. and Van der Burg, E. (2015). True and perceived synchrony are preferentially associated with particular sensory pairings, *Sci. Rep.* **5**, 17467. DOI:10.1038/srep17467.

Ohlsson, S. (2012). The problems with problem solving: reflections on the rise, current status, and possible future of a cognitive research paradigm, *J. Problem Solv.* **5**, 101–128.

Pearl, D., Yodashkin-Porat, D., Katz, N., Valevski, A., Aizenberg, D., Sigler, M., Weizman, A. and Kikinzon, L. (2009). Differences in audiovisual integration, as measured by McGurk phenomenon, among adult and adolescent patients with schizophrenia and age-matched healthy control groups, *Compr. Psychiatry* **50**, 186–192.

Powers, A. R., Hillock, A. R. and Wallace, M. T. (2009). Perceptual training narrows the temporal window of multisensory binding, *J. Neurosci.* **29**, 12265–12274.

Powers, A. R., Hevey, M. A. and Wallace, M. T. (2012). Neural correlates of multisensory perceptual learning, *J. Neurosci.* **32**, 6263–6274.

Raven, J. C. (1965). *Advanced Progressive Matrices: Sets I and II*. Lewis, London, UK.

Ross, L. A., Saint-Amour, D., Leavitt, V. M., Molholm, S., Javitt, D. C. and Foxe, J. J. (2007). Impaired multisensory processing in schizophrenia: deficits in the visual enhancement of speech comprehension under noisy environmental conditions, *Schizophr. Res.* **97**, 173–183.

Russo, N., Foxe, J. J., Brandwein, A. B., Altschuler, T., Gomes, H. and Molholm, S. (2010). Multisensory processing in children with autism: high-density electrical mapping of auditory–somatosensory integration, *Autism Res.* **3**, 253–267.

Schall, J. D. and Hanes, D. P. (1993). Neural basis of saccade target selection in frontal eye field during visual search, *Nature* **366**, 467–469.

Schooler, J. W. and Melcher, J. (1995). The ineffability of insight, in: *The Creative Cognition Approach*, S. M. Smith, T. B. Ward and R. A. Finke (Eds), pp. 97–133. MIT Press, Cambridge, MA, USA.

Sekuler, R., Sekuler, A. B. and Lau, R. (1997). Sound alters visual motion perception, *Nature* **385**, 308.

Shams, L. (2002). Integration in the brain — the subconscious alteration of visual perception by cross-modal integration, *Sci. Consc. Rev.* **1**, 1–4.

Spearman, C. and Wynn-Jones, L. (1951). *Human Ability*. Macmillan, London, UK.

Spence, C., Baddeley, R., Zampini, M., James, R. and Shore, D. I. (2003). Multisensory temporal order judgments: when two locations are better than one, *Percept. Psychophys.* **65**, 318–328.

Spence, C. and Squire, S. (2003). Multisensory integration: maintaining the perception of synchrony, *Curr. Biol.* **13**, R519–R521.

Stein, B. E. and Stanford, T. R. (2008). Multisensory integration: current issues from the perspective of the single neuron, *Nat. Rev. Neurosci.* **9**, 255–266.

Stevenson, R. A. and James, T. W. (2009). Audiovisual integration in human superior temporal sulcus: inverse effectiveness and the neural processing of speech and object recognition, *Neuroimage* **44**, 1210–1223.

Stevenson, R. A. and Wallace, M. T. (2013). Multisensory temporal integration: task and stimulus dependencies, *Exp. Brain Res.* **227**, 249–261.

Stevenson, R. A., Zemtsov, R. K. and Wallace, M. T. (2011). Multisensory illusions and the temporal binding window, *Iperception* **2**, 903.

Stevenson, R. A., Zemtsov, R. K. and Wallace, M. T. (2012). Individual differences in the multisensory temporal binding window predict susceptibility to audiovisual illusions, *J. Exp. Psychol. Hum. Percept. Perform.* **38**, 1517–1529.

Stevenson, R. A., Wilson, M. M., Powers, A. R. and Wallace, M. T. (2013). The effects of visual training on multisensory temporal processing, *Exp. Brain Res.* **225**, 479–489.

Stevenson, R. A., Siemann, J. K., Woynaroski, T. G., Schneider, B. C., Eberly, H. E., Camarata, S. M. and Wallace, M. T. (2014a). Brief report: arrested development of audiovisual speech perception in autism spectrum disorders, *J. Autism Dev. Disord* **44**, 1470–1477.

Stevenson, R. A., Segers, M., Ferber, S., Barense, M. D. and Wallace, M. T. (2014b). The impact of multisensory integration deficits on speech perception in children with autism spectrum disorders, *Front. Psychol.* **5**, 379. DOI:10.3389/fpsyg.2014.00379.

Stevenson, R. A., Siemann, J. K., Schneider, B. C., Eberly, H. E., Woynaroski, T. G., Camarata, S. M. and Wallace, M. T. (2014c). Multisensory temporal integration in autism spectrum disorders, *J. Neurosci.* **34**, 691–697.

Stevenson, R. A., Segers, M., Ferber, S., Barense, M. D., Camarata, S. and Wallace, M. T. (in press). Keeping time in the brain: autism spectrum disorder and audiovisual temporal processing, *Autism Res.*, DOI:10.1002/aur.1566.

Stone, J. V., Hunkin, N. M., Porrill, J., Wood, R., Keeler, V., Beanland, M., Port, M. and Porter, N. R. (2001). When is now? Perception of simultaneity, *Proc. R. Soc. Lond. B Biol. Sci.* **268**, 31–38.

Sumby, W. H. and Pollack, I. (1954). Visual contribution to speech intelligibility in noise, *J. Acoust. Soci. Am.* **26**, 212–215.

Szycik, G. R., Münte, T. F., Dillo, W., Mohammadi, B., Samii, A., Emrich, H. M. and Dietrich, D. E. (2009). Audiovisual integration of speech is disturbed in schizophrenia: an fMRI study, *Schizophr. Res.* **110**, 111–118.

Thomas, L. E. and Lleras, A. (2007). Moving eyes and moving thought: on the spatial compatibility between eye movements and cognition, *Psychonom. Bull. Rev.* **14**, 663–668.

Vaillant-Molina, M. and Bahrick, L. E. (2012). The role of intersensory redundancy in the emergence of social referencing in 51/2-month-old infants, *Dev. Psychol.* **48**, 1–9.

Van der Smagt, M. J., van Engeland, H. and Kemner, C. (2007). Brief report: can you see what is not there? Low-level auditory–visual integration in autism spectrum disorder, *J. Autism Dev. Disord.* **37**, 2014–2019.

Van Eijk, R. L., Kohlrausch, A., Juola, J. F. and Van de Par, S. (2008). Audiovisual synchrony and temporal order judgments: effects of experimental method and stimulus type, *Percept. Psychophys.* **70**, 955–968.

Van Wassenhove, V., Grant, K. W. and Poeppel, D. (2007). Temporal window of integration in auditory–visual speech perception, *Neuropsychologia* **45**, 598–607.

Vatakis, A. and Bakou, A. E. (2015). Distorted multisensory experiences of order and simultaneity, in: *Time Distortions in Mind: Temporal Processing in Clinical Populations*, A. Vatakis and M. Allman (Eds), pp. 1–36. Brill, Leiden, The Netherlands.

Vatakis, A. and Spence, C. (2006). Audiovisual synchrony perception for music, speech, and object actions, *Brain Res.* **1111**, 134–142.

Vatakis, A. and Spence, C. (2010). Audiovisual temporal integration for complex speech, object-action, animal call, and musical stimuli, in: *Multisensory Object Perception in the Primate Brain*, M. J. Naumer and J. Kaiser (Eds), pp. 95–121. Springer-Verlag, Berlin & Heidelberg, Germany.

Vatakis, A., Navarra, J., Soto-Faraco, S. and Spence, C. (2008). Audiovisual temporal adaptation of speech: temporal order versus simultaneity judgments, *Exp. Brain Res.* **185**, 521–529.

Visser, E., Zwiers, M. P., Kan, C. C., Hoekstra, L., Van Opstal, A. J. and Buitelaar, J. K. (2013). Atypical vertical sound localization and sound-onset sensitivity in people with autism spectrum disorders, *J. Psychiatry Neurosci.* **38**, 398–406.

Vroomen, J. and Keetels, M. (2010). Perception of intersensory synchrony: a tutorial review, *Atten. Percept. Psychophys.* **72**, 871–884.

Vroomen, J., Keetels, M., De Gelder, B. and Bertelson, P. (2004). Recalibration of temporal order perception by exposure to audio-visual asynchrony, *Cogn. Brain Res.* **22**, 32–35.

Wallace, M. T. and Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities, *Neuropsychologia* **64**, 105–123.

Woynaroski, T. G., Kwakye, L. D., Foss-Feig, J. H., Stevenson, R. A., Stone, W. L. and Wallace, M. T. (2013). Multisensory speech perception in children with autism spectrum disorders, *J. Autism Dev. Disord.* **43**, 2891–2902.

Zabelina, D. L. and Beeman, M. (2013). Short-term attentional perseveration associated with real-life creative achievement, *Front. Psychol.* **4**, 191. DOI:10.3389/fpsyg.2013.00191.

Zabelina, D. L., O'Leary, D., Pornpattananangkul, N., Nusslock, R. and Beeman, M. (2015a). Creativity and sensory gating indexed by the P50: selective versus leaky sensory gating in divergent thinkers and creative achievers, *Neuropsychologia* **69**, 77–84.

Zabelina, D., Saporta, A. and Beeman, M. (2015b). Flexible or leaky attention in creative people? Distinct patterns of attention for different types of creative thinking, *Mem. Cogn.* **1**, 1–11.

Zampini, M., Shore, D. I. and Spence, C. (2003). Audiovisual temporal order judgments, *Exp. Brain Res.* **152**, 198–210.

Zampini, M., Guest, S., Shore, D. I. and Spence, C. (2005). Audio-visual simultaneity judgments, *Percept. Psychophys.* **67**, 531–544.

Zmigrod, S. and Hommel, B. (2011). The relationship between feature binding and consciousness: evidence from asynchronous multi-modal stimuli, *Consc. Cogn.* **20**, 586–593.

Zmigrod, S. and Zmigrod, L. (2015). Zapping the gap: reducing the multisensory temporal binding window by means of transcranial direct current stimulation (tDCS), *Consc. Cogn.* **35**, 143–149.

Zmigrod, S., De Sonneville, L. M. J., Colzato, L. S., Swaab, H. and Hommel, B. (2013). Cognitive control of feature bindings: evidence from children with autistic spectrum disorder, *Psychol. Res.* **77**, 147–154.

Zmigrod, S., Zmigrod, L. and Hommel, B. (2015). Zooming into creativity: individual differences in attentional global-local biases are linked to creative thinking, *Front. Psychol.* **6**, 1647. DOI:10.3389/fpsyg.2015.01647.