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Research report

ERP-pupil size correlations reveal how bilingualism enhances cognitive flexibility

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ABSTRACT

A bilingual upbringing has been shown to enhance executive control, but the neural mechanisms underpinning such effect are essentially unknown. Here, we investigated whether monolingual and bilingual toddlers differ in semantic processing efficiency and their allocation of attention to expected and unexpected visual stimuli. We simultaneously recorded event-related brain potentials (ERPs) and pupil size in monolingual and bilingual toddlers presented with (spoken) word–picture pairs. Although ERP effects elicited by semantic relatedness were indistinguishable between the two children groups, pictures unrelated to the preceding word evoked greater pupil dilation than related pictures in bilinguals, but not in monolinguals. Furthermore, increasing pupil dilation to unrelated pictures was associated with decreasing N400 amplitude in bilinguals, whereas the monolingual toddlers showed the opposite association. Hence, attention to unexpected stimuli seems to hamper semantic integration in monolinguals, but to facilitate semantic integration in bilinguals, suggesting that bilingual toddlers are more tolerant to variation in word–referent mappings. Given the link between pupil dilation and norepinephrine-driven cognitive efficiency, correlations between ERP amplitude and concurrent pupil dilation provide new insights into the neural bases of the bilingual cognitive advantage.

1. Introduction

A bilingual upbringing is believed to have both beneficial and detrimental consequences for language and cognitive development (Bialystok, 2009). The best established beneficial cognitive consequence of bilingualism put forward in recent years is in the domain of executive control. Numerous studies have shown that bilinguals outperform monolingual peers on tasks that require executive control from as early as 7 months (Bialystok, 2004; Kovacs and Mehler, 2009; Poulin-Dubois et al., 2011). The assumption is that bilinguals have to maintain higher levels of attention and control on language production and perception and that such continuous load on executive control results in an increase in its capacity (Abutalebi and Green, 2008; Bialystok et al., 2008).

In our previous studies, we showed that bilingual toddlers and adults detect a language switch faster than their monolingual peers, even though the switch is perceptually salient in both groups (Kuipers and Thierry, 2010, 2012). When presented with an unexpected switch in language, the event-related brain potential (ERP) elicited by spoken words distinguished between languages at least 100 msec earlier (i.e., in the P2 time-range) in bilinguals than monolinguals in both age groups. Such better distinction between speech sounds by bilinguals may be realized through better encoding in the auditory neural pathway. Indeed, speech sounds appear to be more robustly

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encoded in the brainstem of bilinguals than in those of monolinguals (Krizman et al., 2012).

Given that bilingual children (and adults) process speech differently than their monolingual peers, here, we investigated a) whether this generalizes to semantic processing of visual stimuli, b) whether the language groups differ in attention allocation, and c) how this relates to semantic processing efficiency.

It is well-established that processing a word (e.g., car) primes semantically related concepts (e.g., bus; Collins and Loftus, 1975) and that such priming is reflected in the amplitude of the N400 in adults (Kutas and Federmeier, 2000), but also in infants as young as 12 months (Friedrich and Friederici, 2010). N400 amplitude becomes more negative with decreasing semantic relatedness between two stimuli and is classically associated with the effort involved in semantic integration of a stimulus within its context (Chwilla et al., 1995).

Although pupil size is classically associated with allocation of attention and cognitive effort (Beatty, 1982), it is recently also associated with the firing rate of Locus Coeruleus (LC) neurons (Aston-Jones and Cohen, 2005), which are the sole source of norepinephrine (NE) in the forebrain (Samuels and Szabadi, 2008; Sara, 2009). Pupil size is indirectly controlled by the LC through NE receptors in the iris dilator muscle (Yoshitomi et al., 1985) and the Edinger–Westphal nucleus (Breen et al., 1983). Accordingly, pupil size is increasingly used as an estimation of NE levels in the brain (Einhauser et al., 2008; Gabay et al., 2011; Jepma and Nieuwenhuis, 2011).

Activity of the LC–NE system is also hypothesized to play a central role in task efficiency and cortical arousal (Aston-Jones and Cohen, 2005; Berridge and Waterhouse, 2003; Usher et al., 1999). NE has excitatory and inhibitory effects on neural transmission through the different types of NE receptors (α1, α2, and β types) leading to decreasing spontaneous firing and increasing stimulus evoked firing (Bloom, 1979; Foote et al., 1975). Hence, the LC–NE system influences how effective a stimulus is processed by the brain.

In the current study, toddlers of a monolingual or bilingual background were presented with a spoken word followed by a picture that either matched or mismatched the meaning of the word while ERPs and pupil size were recorded simultaneously (cf. Kuipers and Thierry, 2011). The combination of pupil dilation and ERP recordings provides the opportunity to study the relation between allocated attention and efficiency of specific cognitive processes.

We anticipated that language group differences in visual semantic integration would be reflected in the timing and amplitude of the semantic effect in ERP waveforms. Group differences in attention allocation would be reflected in the semantic effect in pupil dilation. Finally, the strength, timing, and direction of the correlation between ERP amplitude and stimulus evoked pupil dilation would reflect the impact LC–NE activity has on particular cognitive processes.

2. Materials and methods

2.1. Participants

Thirteen bilingually raised and 13 monolingually raised 2–3-year olds from North-Wales were included in the analyses. Informed consent was given by caregivers and the study was approved by the Ethics Committee of Bangor University. The monolingual children had an average age of 31 $\pm$ 2 months and had a score of 94% $\pm$ 5% on average on a short version of the McArthur–Bates Communicative Development Inventory (CDI; Hamilton et al., 2000). The bilingual children, also aged 31 $\pm$ 2 months, were exposed to English (average English CDI score 91% $\pm$ 8%) and at least one other European language (Welsh, Hungarian, German, French, or Spanish) from birth. A further 7 children did not provide enough artifact free trials (<20) per condition in both ERP and pupil size averages due to fussiness and/or technical problems.

2.2. Stimuli

Fifty-two color pictures of highly familiar objects or animals were selected from an in-house database. The basic-level English name of each picture was spoken by a woman and digitized at a sampling rate of 44.1 kHz, 16 bit encoding, mono. Average word duration was 687 msec $\pm$ 39 msec, mean familiarity and concreteness ratings of adults were (on a scale from 100 to 700): 563 $\pm$ 19 and 596 $\pm$ 10 (MRC database; Coltheart, 1981), and mean frequency was 455 $\pm$ 132 (out of 1 million words of 2–3-year olds; CHILDES database; Baath, 2010).

2.3. Procedure

The experiment took place in a normally illuminated room (30 cd/m^2 background luminance and 156 cd/m^2 at the screen) to maintain tonic parasympathetic activity, which enables detection of pupil dilation changes within the first second after stimulus onset (Steinhauer et al., 2004). Participants were seated on their caregivers lap at 1.8 m from a high resolution LED 40″ screen (Samsung UE40B80000) and a remote eye-tracker (TOBII X60; 60 Hz sampling rate) was positioned approximately 70 cm from the eyes of the participant. Pictures spanned a maximum of 9° of visual angle. Each trial started with presentation of a fixation cross and the spoken word "look" during which the eye-tracker verified that the child was looking at the fixation before presentation of the prime stimulus (spoken word; min. duration 640 msec), a 100 msec inter stimulus interval, and the target picture presented for a duration of 1200 msec (Fig. 1). If the child did not attend fixation after presentation of the word "look", a movie puppet and song were presented to attract their gaze back to fixation, which was automatically controlled by the eye-tracker and the stimulus computer using E-Prime (Schneider et al., 2002). Auditory stimuli were presented with 60–68 dB intensity via loudspeakers set 2 m in front of the participant. The picture–word pairs were constructed such that each word was paired with a matching picture (e.g., horse–horse; match condition) or an unrelated one (e.g., horse–flower; unrelated condition) avoiding semantic, phonological, and orthographic overlap. Overall, 104 word–picture pairs were presented twice in a random order separated by short breaks every 3–5 min.

2.4. Data acquisition

Event-related potentials (ERP) were continuously sampled at 1 kHz and band-pass filtered between .1 and 200 Hz from