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Performance and ERP components in the equiprobable go/no-go task: Inhibition in children

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The equiprobable go/no-go task lacks the dominant go imperative found in the usual go/no-go task, and hence we previously regarded it as involving little inhibition. However, children have relative difficulty with this task, and demonstrate large frontal no-go N2s. We investigated whether this child N2 plays an inhibitory role, using performance measures to illuminate the link between N2 and inhibition. Forty children aged 8 to 13 were presented with four stimulus blocks each containing 75 go and 75 no-go tone stimuli in random order. A temporal PCA with unrestricted varimax rotation quantified the mean go and no-go ERP component amplitudes. Most identified components were differentially enhanced to go or no-go as in adults, supporting a previously proposed differential processing schema. Between subjects, larger frontocentral no-go N2bs were associated with fewer commission errors. Hence, the no-go N2b in this paradigm can be interpreted as an individual marker of inhibition in children.

Keywords

inhibition, task, no, go, children, equiprobable, erp, components, performance

Disciplines

Education | Social and Behavioral Sciences

Performance and ERP components in the equiprobable Go/NoGo task: Inhibition in children

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Abstract

The equiprobable Go/NoGo task lacks the dominant Go imperative found in the usual Go/NoGo task, and hence we previously regarded it as involving little inhibition. However, children have relative difficulty with this task, and demonstrate large frontal NoGo N2s. We investigated whether this child N2 plays an inhibitory role, using performance measures to illuminate the link between N2 and inhibition. Forty children aged 8 to 13 were presented with four stimulus blocks each containing 75 Go and 75 NoGo tone stimuli in random order. A temporal PCA with unrestricted VARIMAX rotation quantified the mean Go and NoGo ERP component amplitudes. Most identified components were differentially enhanced to Go or NoGo as in adults, supporting a previously-proposed differential processing schema. Between subjects, larger frontocentral NoGo N2bs were associated with fewer commission errors. Hence the NoGo N2b in this paradigm can be interpreted as an individual marker of inhibition in children.

Keywords: Children, Equiprobable Go/NoGo paradigm, ERPs, Performance, Inhibition

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Equiprobable Go/NoGo Task

The equiprobable auditory Go/NoGo paradigm is useful because it provides equal numbers of stimuli in each of two different processing chains, Go and NoGo, allowing efficient generation of ERPs to explore the sequential processing involved (Pfefferbaum, Ford, Weller, & Kopell, 1985). This uncued paradigm, sometimes called a *50% oddball task* (Barry, Kirkaikul, & Hodder, 2000), is intermediate between the common Go/NoGo task (with Go probability > 50%) and the standard oddball paradigm (with target probability < 50%). Early stimulus-probability studies demonstrated the orderly shift in P300 response amplitudes as target probability changed from one of these extremes to the other (Duncan-Johnson & Donchin, 1977; Johnson, 1986), emphasising the underlying processing continuum.

Go/NoGo paradigms are traditionally synonymous with study of the inhibition required to withhold the predominant Go response (e.g., Fonaryova Key, Dove, & Maguire, 2005; Jodo & Kayama, 1992). In essence, the dominant Go responding pattern requires effortful inhibition of that response when a low-probability NoGo stimulus is presented. However, in a study of equiprobable auditory stimulus presentations in the context of the Orienting Reflex (OR), Barry and Rushby (2006) found evidence that the equiprobable paradigm variant differs importantly from the traditional Go/NoGo task in requiring little, if any, inhibition when not responding to the NoGo stimulus. Rather, the electrodermal response indicated that Go stimuli required effortful processing in this task, while NoGo stimuli did not. Nevertheless, those stimuli generated the usual anteriorisation of the NoGo P3 characteristic of the Go/NoGo paradigm. In OR terms, it was therefore conceptualised that the NoGo stimuli in this paradigm are "Indifferent" and the Go stimuli are "Significant", as only the latter required effortful processing. These electrodermal and P3 results, and our interpretation of them, have since been supported in

an equiprobable *visual* Go/NoGo task (Recio, Schacht, & Sommer, 2009). In the absence of

evidence to the contrary, this perspective has been carried forward in a number of our studies

using the equiprobable auditory Go/NoGo task to explore brain dynamics in both adults and

children (Barry, 2009; Barry & De Blasio, 2012; Barry, De Blasio, De Pascalis, & Karamacoska,

2014; Barry, De Blasio, Rushby, & Clarke, 2010; De Blasio & Barry, 2013a, 2013b), ERP

outcomes in adults and children (Barry, De Blasio, & Borchard, 2014), and caffeine effects in

adults (Barry, De Blasio, & Cave, 2014; Barry et al., 2007).

In adults, a range of ERP components are typically elicited in the auditory equiprobable

Go/NoGo. In latency order, peak-picking investigations report a substantial N1, small P2 and

N2 components that are usually apparent as inflection points in the grand mean ERPs, and a

substantial P3 (Barry, 2009; Barry & De Blasio, 2012; Barry et al., 2007, 2010; De Blasio &

Barry, 2013a, 2013b). Utilising Principle Components Analysis (PCA) to quantify the ERP

amplitudes, several components and sub-components have been consistently identified based on

their polarity, latency, and topography (Barry & De Blasio, 2013; Barry, De Blasio, & Borchard,

2014; Barry, De Blasio, & Cave, 2014; Barry, De Blasio, De Pascalis, & Karamacoska, 2014); in

latency order these include N1-1 (a dominant "true" N1 component; Näätänen & Picton, 1987), a

temporal Processing Negativity (PN; Näätänen & Picton, 1987), P2, N2, P3, classic Slow Wave

(SW) and a novel diffuse Late Positivity (LP). As in the peak-picked studies, the P2 and/or N2

components have tended to be small, accounting for little of the variance in the data, and have

been analysed in some studies (Barry & De Blasio, 2013; Barry, De Blasio, & Borchard, 2014),

but not others (Barry, De Blasio, De Pascalis, & Karamacoska, 2014), and are sometimes not

found (Barry, De Blasio, & Cave, 2014).

To date, we have generally found in these PCA studies that the adult N1-1 and the

temporal topography defining PN are greater to Go. The positive P2 shows enhancement to Go,

and demonstrated a frontal negativity in response to NoGo in Barry and De Blasio (2013), less so in Barry, De Blasio, and Borchard (2014), but not in Barry, De Blasio, and Cave (2014); currently we consider the across-Condition component as a combined (Go) P2/(NoGo) N2. The following separate N2 component is enhanced to Go. P3 shows the traditional parietal enhancement to Go and frontocentral enhancement to NoGo. The SW is enhanced to Go, and the LP is substantial only for NoGo.

A Processing Schema

In trying to understand the neurocognitive processing involved, we recently proposed a processing schema for adults in this paradigm (Barry & De Blasio, 2013). We conceptualised the neuropsychological processes involved in this task as a series of sequential processing stages. This begins with sensory processing of the stimulus, contributing to its identification as a task-relevant (rather than extraneous) event, and this sensory processing leads to cognitive categorisation of the stimulus as Go or NoGo. Each of these categorisation outcomes begins a separate processing chain. For Go, effortful processing leading to the button-press response is activated, and the response is produced. For NoGo, our "indifferent" perspective suggested that there is no need for further effortful processing, and the stimulus processing winds down as the subject disengages from the task for the remainder of the interstimulus interval. These stages are similar to those involved in many auditory focussed attention tasks.

In our current conceptualisation of the schema, slightly varied from Barry and De Blasio (2013) in terms of subsequent findings regarding the P2/N2 complex, we hypothesise that early sensory ERP components, such as the mid-latency potentials and subsequent P1 and N1-3 (an early "true" N1 subcomponent; Näätänen & Picton, 1987), which carry only small amounts of variance and are not reliably extracted by PCA, mark the sensory processing or feature analysis (Kok, 1997) aimed at identifying the stimulus event as task-related and worthy of subsequent

attentional processing. The enhancement of N1-1 to Go indicates the beginning of the

identification of the Go/NoGo stimulus, confirmed by the more-temporal Go PN that Näätänen

and Picton (1987) note "lasts during the processing of an attended auditory stimulus" (p. 412).

Kok (1997) sees this activation as using working memory to match stimulus features to the

Go/NoGo task parameters. Subsequent to categorisation of the stimulus as "Go" vs. "NoGo",

the processing chain of each stimulus type is marked by different components. The P2/N2

complex splits into a Go P2 (Crowley & Colrain, 2004) and anterior NoGo N2 (the latter

consistent with Huster, Enriquez-Geppert, Lavallee, Falkenstein, & Herrmann, 2013). In the Go

chain, P2 is followed by a more posterior N2 (consistent with Folstein & van Petten, 2008) and

P3b (consistent with Barry & Rushby, 2006), and a SW, representing directed processing related

to response preparation and execution. In the NoGo chain, the frontal N2 is followed by a

frontocentral P3a (consistent with Barry & Rushby, 2006), and LP. The novel diffuse LP is

considered an indicator of cortical deactivation, marking the end of stimulus processing; this

occurs earlier in NoGo than Go. For brevity, we will hereafter refer to the different Go/NoGo

N2s as N2c and N2b, respectively, following Pritchard, Shappell, and Brandt (1991).

Children in this Task

There is little detailed information on the ERPs of children in this specific task. Barry

and De Blasio (2012) reported a study of prestimulus EEG phase effects on child ERP peak-

picked N1 and P3 amplitudes, and more recently, Barry, De Blasio, and Borchard (2014)

conducted the first PCA investigation to include a child sample in this paradigm. In each, the

same sequence of components was generally noted in children as in adults, although the major

difference from adult morphology was a large frontal negativity overlaying the early

components. Similar increased frontal negativity has also been reported in child samples across

a range of auditory tasks. For instance, Holcomb, Ackerman, and Dykman (1986) reported a

large early broad negativity (100-300 ms) to targets and non-targets in an oddball task. These

data were broadly compatible with the morphology reported for a 15% auditory oddball by

Johnstone, Barry, Anderson, and Coyle (1996). Johnstone, Pleffer, Barry, Clarke, and Smith

(2005) noted a large early frontal negativity, centred on N2, in 10 year olds in a Go/NoGo task

with 30% NoGo probability. In a cued variant of the Go/NoGo task in 9 year olds, Jonkman,

Lansbergen, and Stauder (2003) found elevated negativity in the NoGo N2 window, and elevated

child false alarm rates that they interpreted in terms of a developmental lag in response

inhibition. Given the long-standing association between N2 and inhibition, these data suggest

that the enhanced early negativity in children, particularly that in N2, likely reflects response

inhibition. However, there is a scarcity of relevant studies to clarify this in the equiprobable

Go/NoGo task.

As noted above, in the absence of the dominant Go imperative found in the typical

Go/NoGo task, our previous work in adults, including our proposed processing schema, regarded

this equiprobable task as involving little or no inhibitory processing. However, we were aware

of the greater difficulty that children have in this task compared with adults, apparent in their

poorer reaction time (RT) performance and larger error rates (Barry, De Blasio, & Borchard,

2014), and wondered whether their immature inhibition (Jonkman et al., 2003) could be

important here. Hence this study sought to investigate further the differential processing chains

for Go and NoGo in children in this paradigm, and to use the individual's Go performance

measures of RT and RT variability, and errors of omission (Go) and commission (NoGo), to

illuminate their link with response facilitation and inhibition. In particular, we hypothesised that

these performance measures would improve (i.e., reduce) with age, and that children with

increased N2b amplitudes, likely indicating increased NoGo inhibition, would commit fewer

commission errors, following the work of Falkenstein, Hoormann, and Hohnsbein (1999) in

young adults.

Methods

Participants

Forty children aged between 8 and 13 years ($M = 10.4$, $SD = 1.5$) participated in the study, including 17 (of 18) from the child sample in Barry, De Blasio, and Borchard (2014). Twenty-five were male (15 females), 32 were right-handed (8 left-handed); all were recruited from the local area via newspaper advertisements, and screened for neurological disorders, head injury, learning disability and psychiatric conditions. Participation was voluntary and informed consent was obtained from a parent/guardian in line with a protocol approved by the local ethics committee.

Electrophysiological Recording

Continuous EEG was recorded from 19 scalp sites ($\times$ 20,000 gain), using an electrode cap referenced to linked ears; care was taken to balance ear impedances. Vertical and horizontal electro-oculograms (EOGs) were also recorded from electrodes 2 cm above and below the left eye, and 1 cm beyond the outer canthi ($\times$ 5,000 gain). Tin electrodes were used for both EEG and EOG recordings, and all impedances were below 5 KΩ. Data from 0.03 to 35 Hz (with 12 dB/octave cut-off) were sampled by a 16 bit A/D system (AMLAB II) at 512 Hz, and recorded for later off-line analysis.

Task and Procedure

The children were each presented with four stimulus blocks of an uncued equiprobable auditory Go/NoGo paradigm. Each block contained 75 Go and 75 NoGo tone stimuli in random order. Tones were 1000 and 1500 Hz, all of 50 ms duration with 5 ms rise/fall times, presented binaurally via headphones at 60 dB SPL with a fixed stimulus onset asynchrony of 1,100 ms. Target frequency was counterbalanced between participants. Children responded to Go targets

with a button-press, using their preferred hand, as quickly and accurately as possible – i.e., speed

and accuracy were equally emphasised. Practice trials were provided until understanding of the

task was demonstrated, and short breaks were given between blocks. The children were asked to

fixate a central point on a screen located in front of them throughout the blocks with the aim of

reducing movement artefact.

Data Quantification

The continuous EEG waveforms were low-pass filtered (25 Hz, zero-phase shift, 24

dB/Octave, FIR), epoched (–100 to +800 ms relative to stimulus onset), and baselined (–100 to 0

ms) offline using Neuroscan software (Compumedics, v. 4.5.1). Single trials containing

incorrect responses were excluded; these included commissions in NoGo, omissions in Go, and

following our previous study of children (Barry, De Blasio, & Borchard, 2014), Go trials with

delayed responding (RT > 600 ms). Trials with muscular or other artefact (i.e., activity

exceeding ± 100 μV) were then identified and removed. Mean ERPs for each condition

(Go/NoGo) were derived from the remaining epochs.

Pre- and post-stimulus data (–100 ms to +800 ms) were submitted to PCA using Dien's

ERP PCA toolkit (v. 2.23; Dien, 2010) in MATLAB (The Mathworks, v. 8.0.0.783, R2012b).

Mean Go and NoGo ERPs for each of the 19 electrodes and 40 participants resulted in $2 \times 19 \times 40 = 1520$ cases. Data were half-sampled (230 time-points/variables) to improve the

cases:variables ratio to 6.6, exceeding the minimum suggested by Gorsuch (1983). The PCA

used the covariance matrix with Kaiser normalisation, and all 230 factors were rotated using

VARIMAX, in line with the recommendations of Kayser and Tenke (2003). PCA components

were considered in terms of their latency, polarity, similarity with the raw ERP, and known

stimulus-specific effects, following our earlier work using this methodology. Starting with those

components that accounted for the maximum variance in the data, the peak amplitudes of each

component identified as an ERP were exported for analysis.

Statistical Analysis

To investigate component topography and Go/NoGo effects in the children, a repeated-measures MANOVA was carried out separately for each component, assessing amplitudes at nine core sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4), and examining effects of Condition (Go, NoGo). Each analysis included examination of topography, with the sagittal plane (frontal [F3, Fz, F4], central [C3, Cz, C4] and parietal [P3, Pz, P4]) and coronal plane (left [F3, C3, P3], midline [Fz, Cz, Pz] and right [F4, C4, P4]) as factors. Planned contrasts within the sagittal plane compared frontal (F) versus parietal (P) regions, and their mean (F/P) with central (C) sites. Within the coronal plane, the left (L) versus right (R) regions, and their mean (L/R) versus the midline (M) sites, were analysed. These orthogonal planned contrasts and their interactions provide optimal information on the topographic distribution of the amplitude of each component. Since all contrasts were planned and there were fewer than the degrees of freedom for effect, no Bonferroni-type adjustment to α was necessary (Tabachnick & Fidell, 2013). Also, Greenhouse-Geisser type correction was not necessary because single degree of freedom contrasts are not affected by the violations of sphericity assumptions common in repeated-measures analyses of physiological data (O'Brien & Kaiser, 1985). All *F* tests reported have (1, 39) degrees of freedom, and a level of $p < .05$ was required for significance. Effects approaching significance $(.05 < p \leq .10)$ are also reported, but these are not discussed.

In order to best use the between-subject variability of the 40 children, Pearson correlations were employed to explore the effects of the 8 – 13 year age range in the performance measures: mean RT and the within-child variability of RT responding (using the RT standard deviation across the trials with correct responding), and in the number of errors of omission, delayed responding (RT > 600 ms), and total errors in Go, and commission errors in NoGo.

Links between N2 and each error type were also explored using simple correlations conducted

separately for each condition (Go, NoGo). As an estimate of N2 amplitude, the mean over a

small cluster of electrodes with maximal amplitude was used in order to reduce the impact of

random error at any single site. As the direction of all effects was predicted, one-way

probabilities were used for all correlations; each of these tests had $df = 38$. Because this study

deals with a number of measures, the frequency of Type I errors increases, but not the

probability. For any one variable, 1 in 20 significant results is likely to be a false positive. This

likelihood remains if we assess two variables (e.g., Go N2 and NoGo N2 amplitude) – although

considering the second set increases the expected frequency of Type I errors to 2, the probability

is unchanged (2 in 40 tests = .05). That is, the probability of Type I error is not increased.

Howell (1997) argues that adjusting α levels cannot control for an increase in the frequency of

errors.

Results

Grand Mean ERPs

After deletion of error trials, and rejecting epochs with EEG artefacts, the mean number

of trials accepted and averaged to form Go ERPs was 161.0 ($SD = 44.3$; range 58 – 270), and for

NoGo ERPs, 169.2 ($SD = 49.5$; range 76 – 272); the 5% elevation in NoGo trials did not reach

significance, $p = .078$. Figure 1A shows the grand average ERPs for Go and NoGo at the

midline sites, with the major peaks labelled at Fz. In general these appear comparable with our

previous child ERPs in this paradigm (Barry & De Blasio, 2012; Barry, De Blasio, & Borchard,

2014), with a large N1 around 100 ms, a large N2 around 220 ms, and a large P3 apparent around

340 ms frontally and 400 ms parietally. Go P3 is parietal, and NoGo P3 is frontocentral. P3 is

followed by a frontal-negative/parietal-positive classic SW and a subsequent LP that is larger for

NoGo. Components in the first 300 ms appear to be contained in an early broad frontal

negativity not usually seen in adult ERPs (Barry, De Blasio, & Borchard, 2014).

Figure 1 about here

PCA Outcomes

The first 8 components extracted explained 91.8% of the variance. Figure 2A shows the latency, polarity, and topography of these components. Figure 2B indicates their scaled loadings as a function of time. Figure 2C shows their differential response to Go/NoGo. Together, these characteristics, and their similarity with our previous findings and the wider literature, helped identification. They were labelled (in temporal order) as N1-1, PN, N2b and N2c, P3a and P3b, SW, and a LP. Figure 1B shows the ERPs reconstituted from the 8 components, and these traces correspond well with the raw traces in Figure 1A. Correlations between the grand average voltage and the reconstructed voltage across waveform points ranged upwards from 0.97 for NoGo at Pz. With $df = 228$, all these correlations were significant at $p < .001$.

Figure 2 about here

Component Topography and Go/NoGo Effects

As shown in Figure 2A and Table 1, N1-1 was a negativity with a latency of 107 ms, that was dominant in the midline, particularly parietally (note underlining of effect and probability in Table 1 to indicate reversal), and on the right centrally. Figure 2C shows that the N1-1 was enhanced to Go in the parietal and right central regions. Overall there was a main effect of Condition, with N1-1 enhanced in Go.

Table 1 about here

Figure 2A shows a negativity at 174 ms that was strongly frontal and dominant in the hemispheres, particularly on the right; this was identified as the temporal PN. A frontocentral PN dominance was larger in the hemispheres than midline, and Figure 2C shows this was enhanced in Go. The hemispheric elevation was also greater in Go. There was no overall

Condition effect.

N2b was a negativity at 221 ms that was frontocentral and midline, with the frontal dominance larger in the midline, as seen in Figure 2A. Figure 2C shows that N2b was enhanced on the right in NoGo, particularly centrally. Overall, N2b was larger in NoGo than Go.

N2c was a negativity at 271 ms. As illustrated in Figure 2A, it was frontocentral and midline, with the frontocentral topography enhanced in the midline. An enhancement in the left hemisphere approached significance. Figure 2C shows that the frontocentral and midline topography, and the vertex enhancement, was most apparent in Go. N2c showed some Go reduction in the central right and, due to the greater parietal positivity in Go, was somewhat larger overall in NoGo, but these effects failed to reach significance.

Figure 2A illustrates that P3a was a positivity at 330 ms that was frontal and somewhat midline. Frontal activity was greater in the midline, and central activity was enhanced on the left. Figure 2C shows NoGo enhancements in frontal, central, and midline regions, and also in the frontal midline and vertex, with some (non-significant) increase in the left hemisphere. Overall, P3a was larger in NoGo than Go.

Figure 2A shows P3b as a parietal positivity at 397 ms with a frontal negativity. It was centroparietal, with the parietal enhancement larger in the midline and the central enhancement larger in the hemispheres. Figure 2C indicates that the parietal positivity was significantly greater to Go, particularly in the left hemisphere and midline. P3b showed some increase to Go in the left hemisphere, somewhat more so in the central region, and was somewhat reduced in the midline; these effects approached significance. Go P3b was significantly reduced at the vertex, but overall, P3b was greater to Go.

Occurring at 545 ms, the SW in Figure 2A was a centroparietal positivity with a frontal negativity; their difference was largest in the midline. Figure 2C shows that the sagittal

topography was enhanced in Go, as was activity in the left hemisphere, with a relative midline reduction. The frontal negativity/parietal positivity showed some midline enhancement in Go, while the central positivity was significantly enhanced in the hemispheres. Overall, SW positivity was somewhat larger in Go than NoGo.

The LP occurred at 709 ms. Figure 2A indicates that it was centroparietally positive, and reduced in the midline. The parietal positivity showed some left hemisphere enhancement, and significant enhancement in the midline; the central positivity was reduced in the left hemisphere and midline. Figure 2C shows that in NoGo, the parietal positivity of the LP was enhanced, and the central positivity was larger in the left hemisphere. Overall, the LP was larger in NoGo than Go.

Age and Performance

Table 2 summarises performance data for this sample, and the statistical outcomes of the performance versus age analyses are also presented. Figure 3 shows that Go errors of omission, delayed responses, and the total Go error percentage, each had significant reductions with increasing age, as did NoGo errors of commission. Similarly, mean RT and within-subject RT variability (standard deviation across the accepted trials) both decreased with age.

Table 2 and Figure 3 about here

N2 and Performance

Table 2 reports the N2 versus performance statistics separately for NoGo N2b (computed as the mean amplitude across F4, Fz, and Cz), and Go N2c (computed as the mean amplitude across F3, Fz, and Cz). Figure 4 (top) shows that the children's NoGo commission errors correlated significantly with the NoGo N2b; larger N2b amplitudes were associated with fewer errors. To check that this was not just a joint reflection of developmental changes, NoGo N2b is plotted against age in Figure 4 (bottom). Although NoGo errors reduced over this age range,

NoGo N2b did not ($r = -.04$, ns). As indicated in Table 2, Go N2c showed no relation with the

percentage of omission errors, delayed responding errors, and total errors in Go, nor with Go RT

or RT variability.

Figure 4 about here

Discussion

The ERPs and PCA components found here are similar to our previous adult profiles

(Barry & De Blasio, 2013; Barry, De Blasio, & Borchard, 2014; Barry, De Blasio, & Cave,

2014; Barry, De Blasio, De Pascalis, & Karamacoska, 2014), and comparable to those of our

previous child sample (Barry, De Blasio, & Borchard, 2014) in this uncued equiprobable

auditory Go/NoGo paradigm. The first eight components obtained, in temporal order, were N1-

1, PN, N2b, N2c, P3a, P3b, SW, and LP. These eight components accounted for 91.8 % of the

variance in the 230 data points representing the ERPs from 100 ms before stimulus onset to 800

ms after onset. They formed reconstituted ERPs that closely approximated the original ERPs,

displaying trivial and non-systematic differences attributable to the non-included variance.

Comparison with Previous Results

The major differences between the components shown in Figure 2A and our previous

adult PCA outcomes in this paradigm (Barry & De Blasio, 2013; Barry, De Blasio, & Borchard,

2014; Barry, De Blasio, & Cave, 2014; Barry, De Blasio, De Pascalis, & Karamacoska, 2014) is

that here we found no evidence of a P2, but rather a separate early N2b component. Further,

rather than one P3 with differential Go/NoGo topography, two separate P3s were obtained, here

labelled P3a (NoGo) and P3b (Go) in line with Barry and Rushby (2006). Relative to our

previous *child* PCA results (Barry, De Blasio, & Borchard, 2014), the present sequence of

components is very similar. We previously reported both a P2 at 209 ms, and an N2 at 264 ms,

labelled as such by analogy from our adult data in that study. That child "P2" had a parietal

positivity, but the frontal negativity accompanying the positivity, and the similarity in latency to the present N2b, suggests that it better fitted the N2b label. The present separate P3a and P3b components are similar to those previous child findings.

Child Go/NoGo Effects

Most of the child ERP components found here showed differential enhancement to Go or NoGo as in our earlier adult investigations, supporting the differential processing schema proposed in our first adult Go/NoGo PCA study (Barry & De Blasio, 2013). Interestingly, the separation of the Go and NoGo N2s and P3s match the typical within-component task differences in adults (in N2 see Folstein & van Petten, 2008; Huster et al., 2013; Pritchard et al., 1991; and in P3 see Barry & De Blasio, 2013; Barry, De Blasio, & Borchard, 2014; Barry, De Blasio, & Cave, 2014; Barry, De Blasio, De Pascalis, & Karamacoska, 2014; Barry & Rushby, 2006). In NoGo we obtained an enhanced frontal N2 and P3; we identified these as N2b and P3a respectively. In Go we found an enhanced and more posterior (vertex) N2, and posterior P3; these were identified as N2c and P3b, respectively, and each peaked later than their NoGo counterpart.

Overall, the sequence of components and their differential patterning with Go versus NoGo task requirements allows us to confirm the general outline of our processing schema in this equiprobable auditory Go/NoGo paradigm (Barry & De Blasio, 2013), and to refine its detail in relation to child participants (Barry, De Blasio, & Borchard, 2014). As we hypothesised, early sensory processing, such as that reflected in the N1 subcomponents N1-1 and PN, marks the beginning of identification of the Go/NoGo stimulus. Subsequent categorisation of the stimulus as "NoGo" is associated with frontocentral N2b and P3a, and an enhanced LP, while categorisation as "Go" is associated with a more posterior N2c and P3b, and the classic SW.

We conceptualise these as markers of two distinct processing chains. For NoGo, N2b

begins an automatic sequence winding down processing of that stimulus, marked by P3a and LP.

The last is a widespread positivity that Barry and De Blasio (2013) postulated as indicating a

broad cortical deactivation marking the end of stimulus processing – earlier for the NoGo than

Go processing chain. For Go, a substantial N2c replaces a weak N2b, followed by P3b and SW,

representing directed processing related to response preparation and execution. It is interesting

to note that the SW, dominant here to Go as in adults and our previous child study, differs from

the classic adult topography in having reduced frontal negativity; rather, that frontal negativity

occurs in the subsequent LP to Go stimuli. Although not noted previously, this pattern is

apparent in our prior child study (Barry, De Blasio, & Borchard, 2014). Whether this marks a

genuine separation of the frontal negativity and parietal positivity of the classic SW, as long

proposed by some authors (e.g., Loveless, Simpson, & Näätänen, 1987), is beyond the scope of

the present study.

N2b and Inhibition

If N2b marks the beginning of the NoGo processing chain, is it relatable to *inhibition* in

children? We found that NoGo commission errors were reduced in children with larger NoGo

N2bs. We checked that this was not just a joint reflection of developmental changes: NoGo

errors reduced over this age range, but NoGo N2b did not. This provides direct evidence that the

NoGo N2b is associated with better NoGo performance, logically *necessitating* an inhibition

interpretation (Falkenstein et al., 1999) – N2b reflects inhibition of responding to the wrong

stimulus. In our prior adult studies, a separate N2b was not obtained, rather, the combined

P2/N2b was not as distinctly separated by condition, showing only a NoGo frontal negativity

overlaying the P2 (consistent with the *indifferent* stimulus interpretation in adults; Barry &

Rushby, 2006). Further exploration of this potential developmental shift, from the inhibitory

child N2b to indifferent adult P2/N2b in the NoGo processing chain in this paradigm, would be

interesting. For example, if time pressure was increased by instructions emphasising speed of response and producing an increase in NoGo errors, a similar link might be expected in adults.

Go Performance

Performance in the Go chain was, as expected, related directly to age: RT, RT variability, and the occurrence of Go omission errors (both misses and late responses) each decreased with increasing age, similar to findings in traditional Go/NoGo tasks (e.g., Johnstone et al., 2007). Go omission errors were not related to Go N2c amplitude here, suggesting that the role of the N2c component is very different from that of the NoGo N2b.

Conclusion

This study has confirmed that the neuropsychological processing schema developed by Barry and De Blasio (2013) in adults is generally useful in understanding the sequential processing shown by children in the uncued equiprobable auditory Go/NoGo task. The results also help explain why this task is harder for children than adults, showing the need for children to inhibit their responding to the NoGo stimulus in this equiprobable task, apparent in an inhibitory frontocentral N2b. Children showing a larger N2b were better able to inhibit responding to NoGo stimuli and produced fewer commission errors. This separate N2b has not been obtained in adults in this paradigm, compatible with our long-standing perspective that inhibition has not been important for adequate adult functioning (Barry & Rushby, 2006). This apparent shift from childhood inhibition to adult indifference in NoGo processing in this equiprobable auditory task will require careful investigation to confirm the validity of our previous interpretation of adult processing and/or to establish the details of the change over age.

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Figure Legends

Figure 1. Panel A: Mean ERPs at the midline sites are shown for Go (black) and NoGo (grey), with major components labelled at Fz. Panel B: The corresponding reconstituted ERPs, the sum of the first eight components identified in the PCA; these are highly similar to the raw ERPs.

Figure 2. Panel A: Topographic headmaps and factor information for the grand mean identified PCA components. Panel B: Scaled PCA factor loadings (across Go/NoGo conditions) are presented for each component. Panel C shows topographic headmaps for components in Go and NoGo conditions.

Figure 3. Behavioural responses as a function of age.

Figure 4. Top: Children's NoGo commission errors correlated significantly with the NoGo N2b amplitude. Bottom: NoGo N2b amplitude did not reduce with age.

Table 1

Grand Mean ERP Component Topography and Go/NoGo Effects

Effect	N1-1 F	p	η_p^2	PN F	p	η_p^2	N2b F	p	η_p^2	N2c F	p	η_p^2	P3a F	p	η_p^2	P3b F	p	η_p^2	SW F	p	η_p^2	LP F	p	η_p^2
F > P				125.43	<.001	.76	30.21	<.001	.44	21.43	<.001	.35	12.04	.001	.24	63.36	<.001	.62	7.78	.008	.17	14.53	<.001	.27
C > F/P				55.42	<.001	.59	25.92	<.001	.40	8.00	.007	.17				12.05	.001	.24	30.14	<.001	.44	87.05	<.001	.69
L < R				9.54	.004	.20				3.87	.056	.09												
M > L/R	19.80	<.001	.34	121.70	<.001	.76	5.80	.021	.13	8.93	.005	.19	3.39	.073	.08							11.15	.002	.22
F > P × L < R																						3.85	.057	.09
F > P × M > L/R	7.94	.008	.17	16.07	<.001	.29	11.24	.002	.22	7.13	.011	.15	19.18	<.001	.33	14.32	.001	.27	74.43	<.001	.66	57.58	<.001	.60
C > F/P × L < R	21.28	<.001	.35										4.89	.033	.11							8.43	.006	.18
C > F/P × M > L/R				49.94	<.001	.56				7.88	.008	.17				5.21	.028	.12				14.01	.001	.26
Go > NoGo × F > P	5.03	.031	.11							8.91	.005	.19	21.65	<.001	.36	46.01	<.001	.54	4.18	.048	.10	4.99	.031	.11
Go > NoGo × C > F/P										11.85	.001	.23	18.03	<.001	.32				35.65	<.001	.48			
Go > NoGo × L < R							7.14	.011	.15				3.65	.063	.09	3.99	.053	.09	7.62	.009	.16			
Go > NoGo × M > L/R				6.73	.013	.15				17.34	<.001	.31	5.93	.020	.13	3.26	.079	.08	5.18	.028	.12			
Go > NoGo × F > P × L < R																11.15	.002	.22						
Go > NoGo × F > P × M > L/R				13.31	.001	.25							4.09	.050	.09	27.98	<.001	.42	3.15	.084	.07			
Go > NoGo × C > F/P × L < R	5.18	.028	.12				4.49	.040	.10	3.35	.075	.08				3.37	.074	.08				4.41	.042	.10
Go > NoGo × C > F/P × M > L/R				15.70	<.001	.29				24.48	<.001	.39	11.13	.002	.22	18.35	<.001	.32	7.12	.011	.15			
Go > NoGo	19.84	<.001	.34				7.00	.012	.15	3.38	.074	.08	4.92	.032	.11	38.25	<.001	.50	3.12	.085	.07	23.87	<.001	.38

Note. Significant effects are indicated with bold *p* values. Underlined statistical results indicate a reversal of the corresponding underlined effect or interaction. F = frontal; P = parietal; C = central; L = left hemisphere; R = right hemisphere; M = midline.

Table 2

Performance Data and Statistics

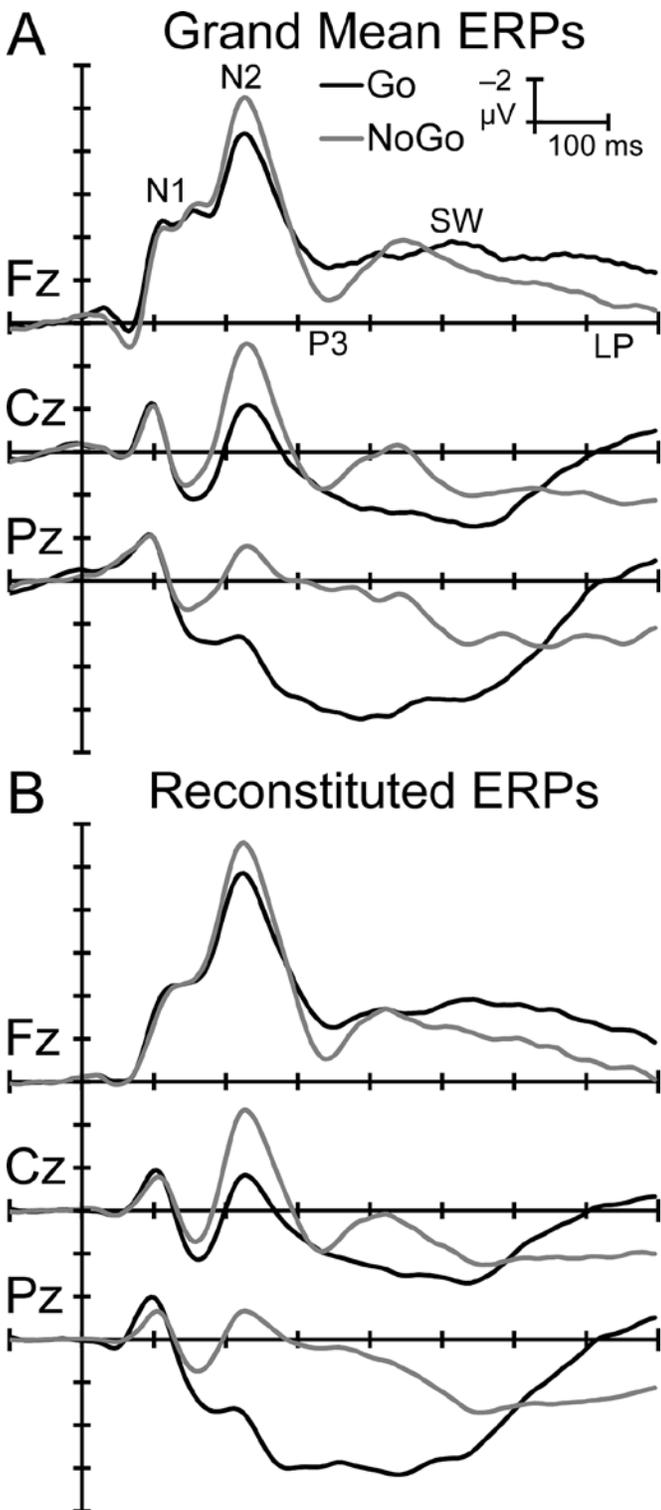|	Go Error (%)			NoGo Error (%)	Go RT (ms)	
	Omissions	RT > 600 ms	Total	Commissions	Mean	Variability
Performance summary data						
Range	0.3 to 24.8	0.3 to 26.2	1.3 to 49.0	1.0 to 29.8	267.3 to 450.5	64.1 to 141.2
Mean (SD)	6.5 (6.8)	9.7 (6.5)	16.1 (12.5)	7.6 (6.2)	359.4 (33.4)	99.8 (19.4)
Performance versus Age						
Pearson's *r*	−.39	−.40	−.42	−.35	−.27	−.33
p	**.007**	**.005**	**.004**	**.013**	**.049**	**.020**
Performance versus NoGo N2b						
Pearson's *r*	n/a	n/a	n/a	.36	n/a	n/a
p				**.012**		
Performance versus Go N2c						
Pearson's *r*	< −.01	−.11	−.06	n/a	−.09	−.08
p	.492	.247	.358		.282	.303

Note. All *p* values are one-tailed, and significant effects are indicated in bold.
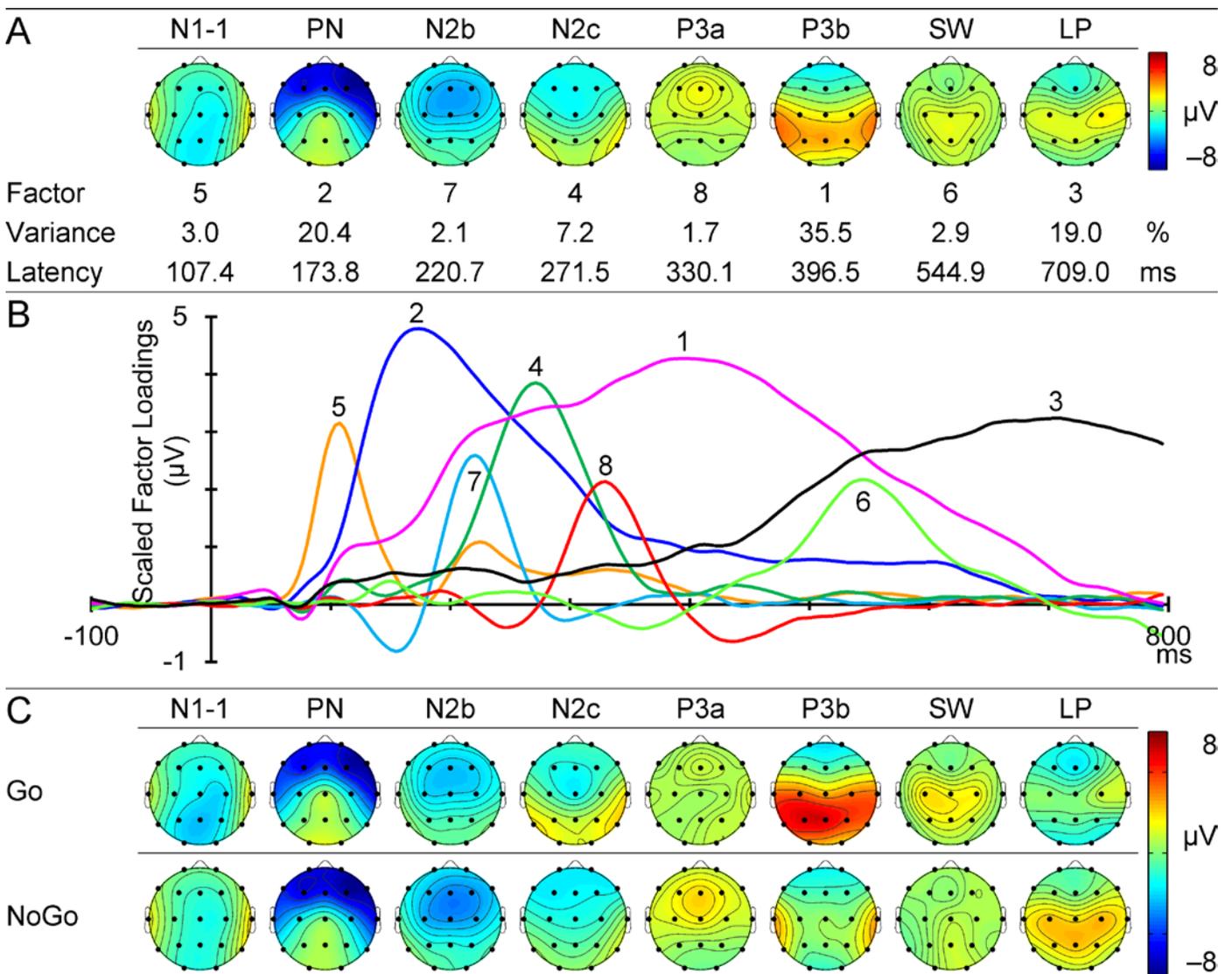
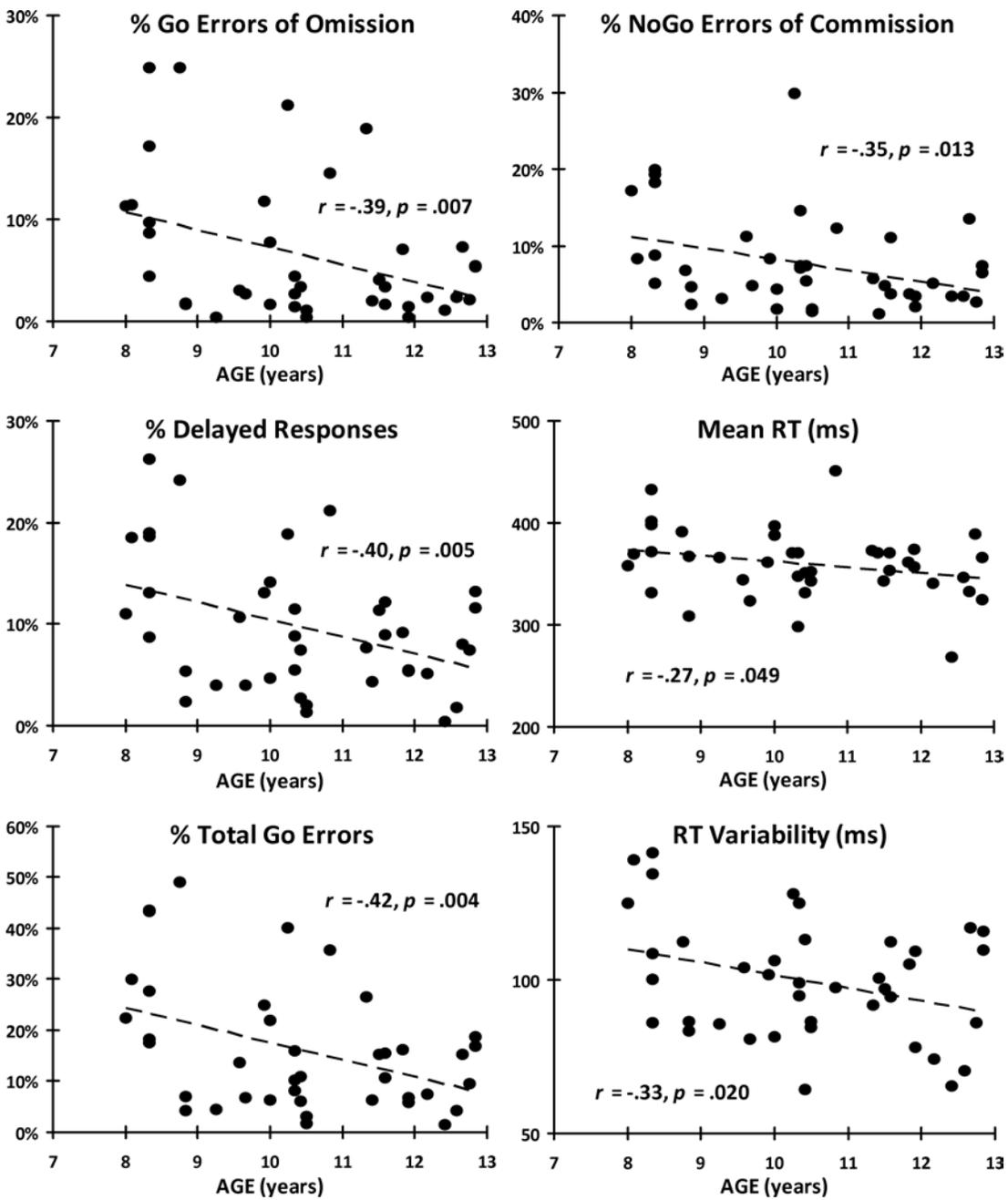*Figure 1*

Figure 2

Figure 3

Figure 4