ICA Provides New Insights into ERP Data: Face Processing in Williams Syndrome

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Abstract

We applied independent component analysis (ICA) to event-related potential (ERP) data that were collected during a face recognition task with two subject groups: normal adults and adults with Williams Syndrome (WMS), a genetic disorder. A previous analysis of the data utilizing traditional ERP analysis techniques identified a late positive component, called the P500. In normal adults, the P500 was linked to recognition of inverted faces, but not upright faces. Unlike normal adults, adults with WMS did not show a P500 effect, though they did show an earlier ERP recognition effect to both upright and inverted faces. These findings were interpreted as evidence that unlike normal adults, WMS adults do not use markedly different brain systems to recognize upright and inverted faces. Using ICA, we determined that the P500 in this task was not unitary, but rather was composed of at least two (in WMS adults) or three (in normal adults) spatially fixed, functionally distinct independent components. We attributed the P500 effect in normal adults to a combination of two of these components, only one of which depends on face orientation. Surprisingly, WMS adults have a similar orientation-dependent independent component, providing evidence that like normal adults, WMS adults do in fact use different brain systems to recognize upright and inverted faces.

1 Introduction

Event-related potentials (ERPs) are electrical potentials on the scalp that are time-locked to particular events. The activity measured by ERPs is primarily caused by currents flowing across the cell membranes of pyramidal cells in the cortex [5]. The effects of many of these cortical sources add up to produce the activity measured at each scalp electrode.

Much of ERP research involves the identification and characterization of components of the observed waveforms. In traditional ERP analysis, components of the response are often identified by the amplitude and latency of averaged response waveforms at individual electrodes. These components are measured by the peak amplitude or mean amplitude (area) of the original average waveforms or of differences between the waveforms of two experimental conditions. If a response is composed of two or more spatially fixed components that overlap in time, it may be difficult to resolve the response into its component parts using traditional methods of ERP analysis. Independent

Component Analysis (ICA), a new approach to linear decomposition [2], can overcome this limitation [6, 7].

In an ERP study of face processing [8, 9], normal adults were compared to adults with Williams Syndrome (WMS), a genetic disorder involving a deletion on chromosome 7. Face processing in WMS is of particular interest because despite their impaired performance in many cognitive domains including other forms of spatial cognition, people with WMS perform in the normal range on face processing tasks [3]. This raises the question of whether the brain systems that mediate face recognition in WMS adults are normally organized, or are organized differently than those in normal adults.

The Mills et al. study, which used traditional methods of ERP analysis, focused on the early components of the response (e.g., N100, N200, and N320). The study also found a single late component, called P500, comprising the activity between 400 and 800 ms. We used ICA to analyze data from the Mills et al. study [9], focusing on the late waves ($t > 400$ ms after stimulus onset). We found that the P500 in this task was not unitary, but consisted of at least two (in WMS adults) or three (in normal adults) functionally distinct independent components.

2 Results of the original Mills et al. study

In an ERP study [8, 9], subjects were shown sequentially-presented photographic pairs of upright or inverted faces and were asked to indicate whether the second face (the target) did or did not match the first face (the prime). Matched pairs were non-identical photographs of the same face; mismatched pairs were photographs of the faces of two different people (same gender). Half of the stimuli were female faces. 16-channel ERPs were recorded while the task was performed by 23 normal adults and by 18 adults* with Williams Syndrome (WMS). For more details on the experimental design, see [9].

Using traditional ERP analysis techniques, Mills et al. found two ways in which normal adults respond differently to upright faces than to inverted faces. For upright faces, a negative component that peaked at 320 ms, called the N320, was larger in response to mismatched targets than to matched targets. This difference, called the N320 match-mismatch effect, was present in response to upright faces but not to inverted faces. In a later positive component that peaked around 500 ms, called the P500, inverted faces elicited a match-mismatch difference but upright faces did not (see Figure 1). These results were interpreted as evidence that normal adults use different brain systems to process upright and inverted faces. In contrast, WMS adults exhibited the N320 match-mismatch effect in response to both upright and inverted faces, and did not exhibit the P500 match-mismatch effect (see Figure 1). Mills et al. viewed the lack of these upright/inverted differences in WMS subjects as supporting the hypothesis that WMS adults do not use different systems for recognizing upright and inverted faces.

3 ICA analysis of the ERP data

In its application to ERP data, independent component analysis (ICA) [2] assumes that the signals recorded at scalp electrodes are weighted sums of spatially fixed independent sources in the brain [6, 7]. ICA attempts to decompose the recorded data in order to recover the original independent source signals. The recovered sources are called independent components.

We performed two separate ICA analyses: one on the normal control group ERPs and one on the WMS group ERPs. The waveforms used in each analysis were grand average waveforms (averages across all subjects) for 16 stimulus conditions: every combination of {upright, inverted}, {matched, mismatched}, {primes, targets}, and {male, female}. Because the original ERP recording used 16 electrodes, the analysis yielded 16 independent components. Of these, we selected those components that were active in the late portion of the ERPs ($t > 400$ ms) and that varied systematically across experimental conditions. We found that the P500 in this task was not unitary, but was composed of at

* Due to a technical problem, ERPs to the primes stimuli were only available for 14 of the 18 adults with WMS. For our ICA analysis, we only included the 14 WMS subjects whose primes data were complete.

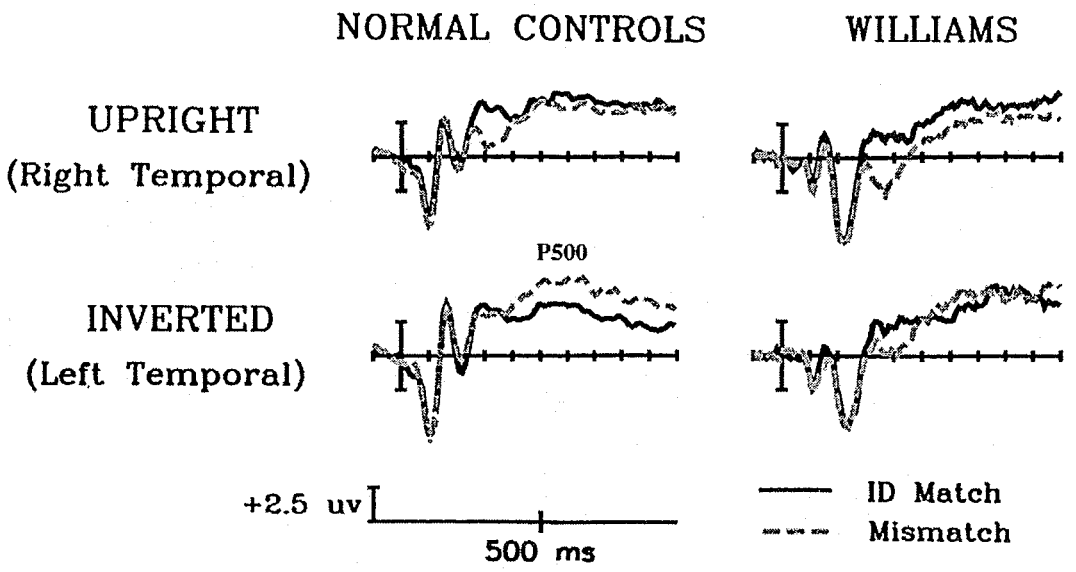

Figure 1: P500 found in the Mills et al. study, shown for matched (solid line) and mismatched (dashed line) targets. Mean area is larger for mismatched than matched targets, only for normal subjects in response to inverted face stimuli (lower left graph). The P500 match-mismatch difference was not significant in the other target conditions shown. Each graph shows just one channel (right temporal or left temporal) of the ERP, but significance tests used data from all channels (see [9]).

least two (in WMS adults) or three (in normal adults) spatially fixed, functionally distinct independent components.

3.1 Normal control group ICA components

The ERP data for the normal control group show a noticeable difference between the responses to primes (first face in the pair) and the responses to targets (second face in the pair). In Figure 2(a,b), the thick black lines are the envelope of all 16 channels of the normal adults' ERP responses to primes and targets. Between about 400 ms and 800 ms, the response to targets is larger than the response to primes.

The SP component. One of the independent components of the normal adults ERPs was consistently positive and roughly constant in amplitude across all eight stimulus conditions and for the entire time range of the late wave. We call this component SP, for sustained positivity. We measured mean SP activation for each condition and each subject, and performed a three-way ANOVA with factors for upright/inverted, match/mismatch, and primes/targets, with repeated measures for the subjects. The ANOVA did not find any significant main effects or interactions for the SP. Figure 2(a) shows the envelope of the SP contribution to all 16 channels. The SP envelope is filled in the time window over which we measured (300 ms $< t <$ 1000 ms).

The P5t component. A second independent component resulting from the normal adults analysis peaked at roughly 500 ms and was much larger in the targets conditions than in the primes conditions. We call this component P5t, where "t" stands for "targets". Figure 2(b) shows the envelope of the P5t in response to primes and targets. The envelope is filled in the time window over which the P5t mean activation was measured (300 ms $< t <$ 800 ms). A three-way ANOVA on the mean activation measures verified that the P5t is significantly larger in response to targets than to primes [$F(1,22) = 7.45$, $p = 0.012$]. There was a marginally significant interaction indicating that the P5t is larger in response to mismatched targets than to matched targets [match/mismatch $\times$ targets/primes: $F(1,22) = 3.604$, $p = 0.071$]. Together, the two components SP and P5t account for 97% of the variance of the 16-channel grand average late-wave data (400 ms $< t <$ 1400 ms) in the targets conditions.

The P7um component. A third independent component showed a much larger response in the upright matched targets condition than in any of the other stimulus conditions. We call it P7um,

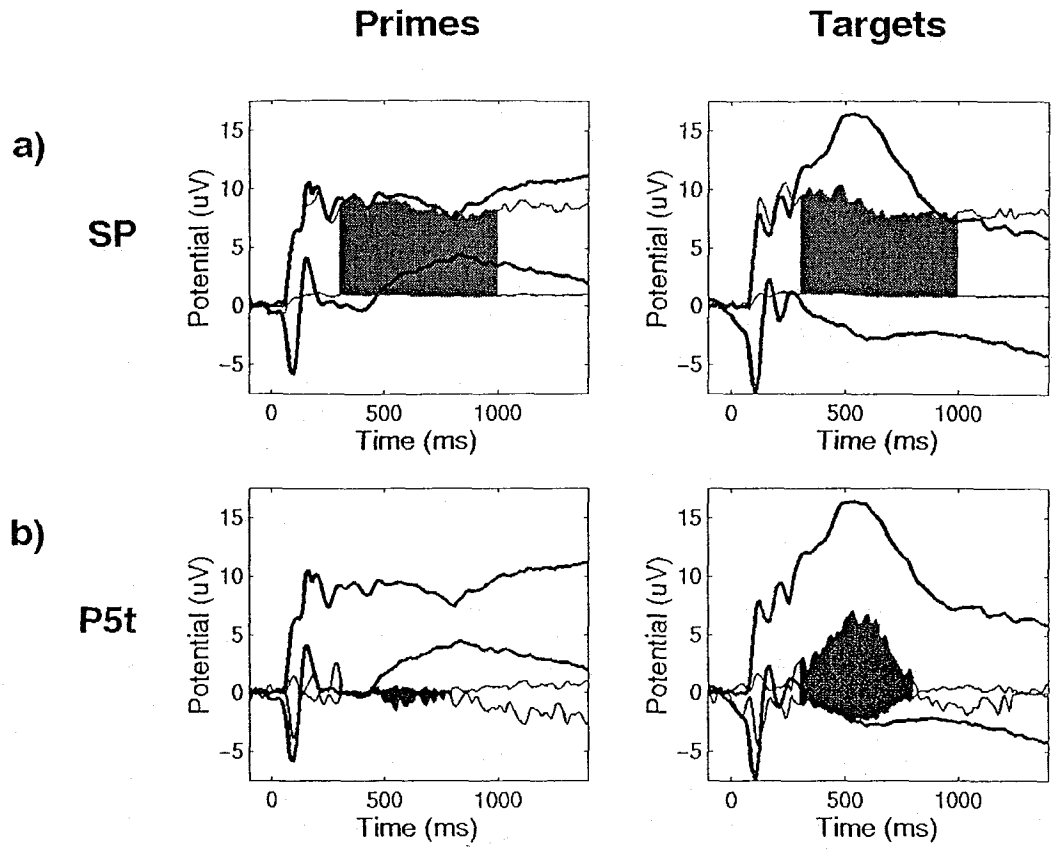

Figure 2. Normal control group envelope plots of the data and the SP and P5t independent components. Left column: responses to prime stimuli. Right column: responses to target stimuli. The thick black lines are the envelope of all 16 channels of grand average data. At each time point, the channel with the largest data value and the channel with the smallest value define the envelope. (a) The envelope of the contribution of the SP component to the data channels is filled in gray. (b) The envelope of the P5t component is filled in dark gray.

where "um" stands for "upright matched". Figure 3 shows the envelope of the P7um (along with the P5t) for the four targets conditions. The envelope of the P7um is filled in light gray. The envelope is filled in the time window over which the P7um mean activation was measured (400 ms $< t <$ 900 ms). We used separate one-tailed paired t-tests to compare the mean P7um activation in the upright matched targets condition with each of the other seven conditions (all other possible combinations of {upright, inverted}, {match, mismatch}, and {primes, targets}). All seven t-tests support the conclusion that the P7um is significantly larger ($\alpha = 0.05$) in the upright matched targets condition.

3.2 WMS group ICA components

The WMS subjects grand average data did not exhibit the same obvious late-wave difference as the control group between responses to targets and responses to primes*. Not surprisingly, the ICA we performed on the WMS group late-wave data did not yield a component with the same functional profile (that was active and inactive in the same conditions) as the P5t in normal subjects.

ICA on the WMS adults data *did* find independent components with the same functional profiles as the normal adults SP and P7um components. We call these the Williams SP and P7um components. Note that ICA was applied separately to the controls data and the WMS data, and the electrode coefficients that define the Williams SP are not equal to the coefficients that define the controls SP. (The Williams P7um and controls P7um are likewise different.) We therefore *cannot* say that the

* This is not to say that the WMS responses to targets and primes were indistinguishable. In the early part of the responses, the primes and targets responses were clearly different.

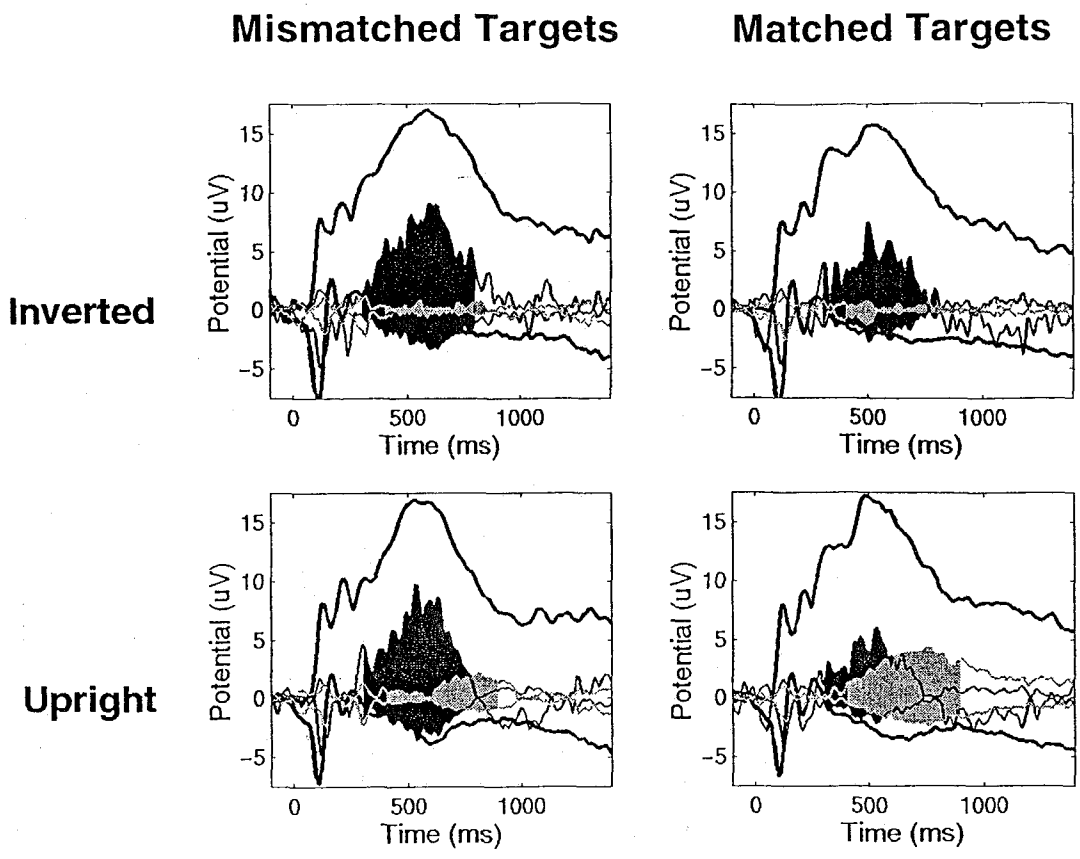

Figure 3: The P500 match-mismatch effect in normal adults explained by a combination of the P5t and the P7um. The P5t (envelope filled in dark gray) has a larger activation in response to mismatched target stimuli (left column) than to matched target stimuli (right column). In the upright targets conditions (bottom row), this match-mismatch difference is offset by the presence of the P7um (envelope filled in light gray), which is most active in response to upright matched targets.

Williams SP and P7um are the *same* components as the controls SP and P7um. However, we *can* say that they are functionally analogous, because they are correspondingly active and inactive in response to the same stimulus conditions.

The Williams SP component. The Williams SP component was consistently positive and roughly constant in amplitude across all eight stimulus conditions and for the entire time range of the late wave. A three-way ANOVA on the mean Williams SP activation (same factors and time window as controls SP) did not find any significant main effects or interactions.

The Williams P7um component. The Williams P7um component was larger in the upright matched targets condition than in any of the other stimulus conditions. Figure 4 shows the envelope of the Williams P7um for the four targets conditions. The envelope of the P7um is filled in light gray (same time window as controls P7um). We used separate one-tailed paired t-tests to compare the mean Williams P7um activation in the upright matched targets condition with each of the seven other stimulus conditions. The difference was significant ($\alpha = 0.05$) for six of the seven conditions, and was marginally significant ($p = 0.055$) for the seventh condition (the inverted matched targets condition).

3.3 Scalp Maps

Figure 5 shows the scalp maps for the three normal group components and the two WMS group components. Both the Williams SP and the Williams P7um are more anterior than the functionally analogous controls SP and controls P7um components. Structural studies of the brains in people with WMS have observed that posterior areas of the WMS brain are abnormally reduced in volume [3]. It

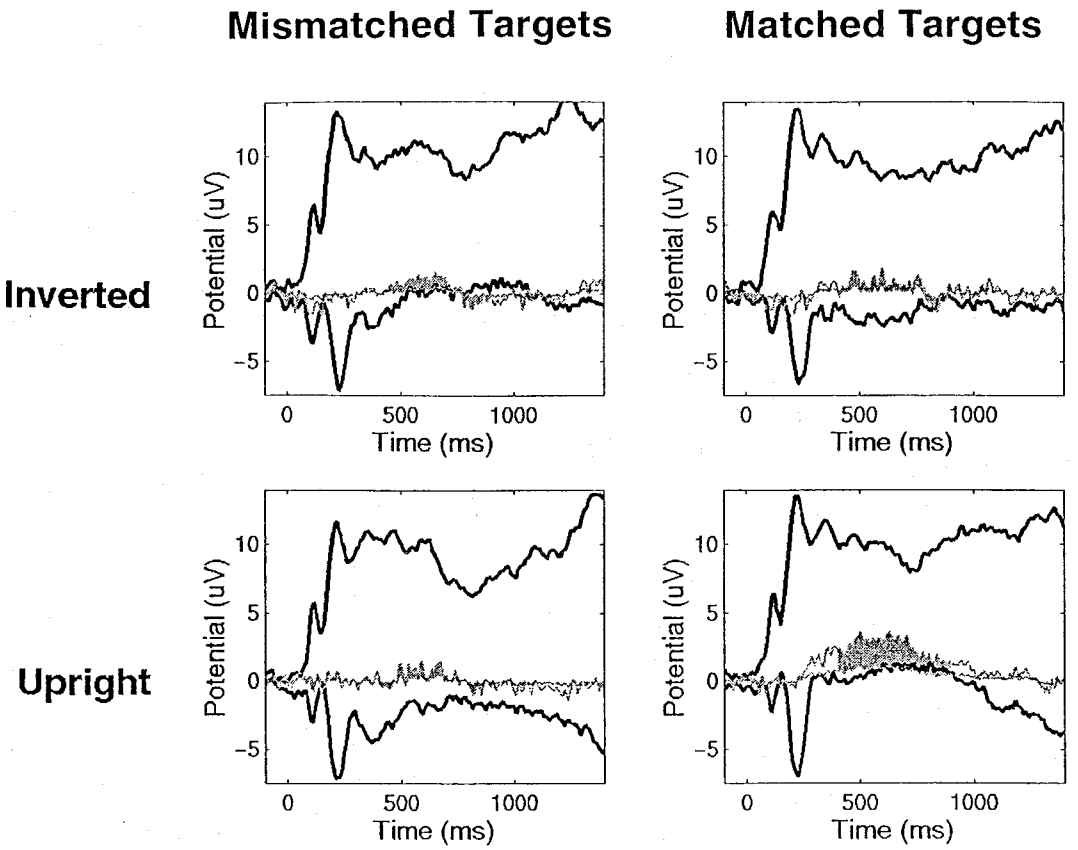

Figure 4: The Williams P7um. Like the controls P7um, the Williams P7um (envelope filled in light gray) is more active in the upright matched targets condition than in any of the other seven experimental conditions. (Only the four targets conditions are shown here.)

has been hypothesized that these posterior structural abnormalities could lead to an anterior displacement of the brain systems that underlie face processing in WMS [9]. The differences between the controls and WMS scalp maps in Figure 5 are consistent with this hypothesis.

4 Methods

In the targets conditions, ERP averages only included trials in which the subject responded correctly (with the correct button indicating match or mismatch). Trials contaminated by eye artifact were removed prior to averaging, as described in [9].

The "infomax" ICA algorithm [2] that we used exploits temporal independence to perform blind separation. Infomax ICA uses gradient ascent to find a square unmixing matrix that maximizes the joint entropy of a nonlinearly transformed ensemble of zero-mean input vectors. For more information on the use of ICA for analysis of grand average ERP data and the assumptions it entails, see [7].

We performed ICA analysis on the grand average ERP from 100 ms before stimulus onset through 1400 ms after stimulus onset. We chose to end the time window for the analysis at 1400 ms because the stimulus was removed at 1500 ms, and eye artifacts were not removed from the data after that time. The choice of 1400 ms instead of 1500 ms was somewhat arbitrary; ICA analysis using 1500 ms instead yielded similar results.

5 Discussion

We approached this analysis with the intent of determining what light ICA, a new method for ERP analysis, could shed on an existing data set that had already been analyzed using traditional ERP

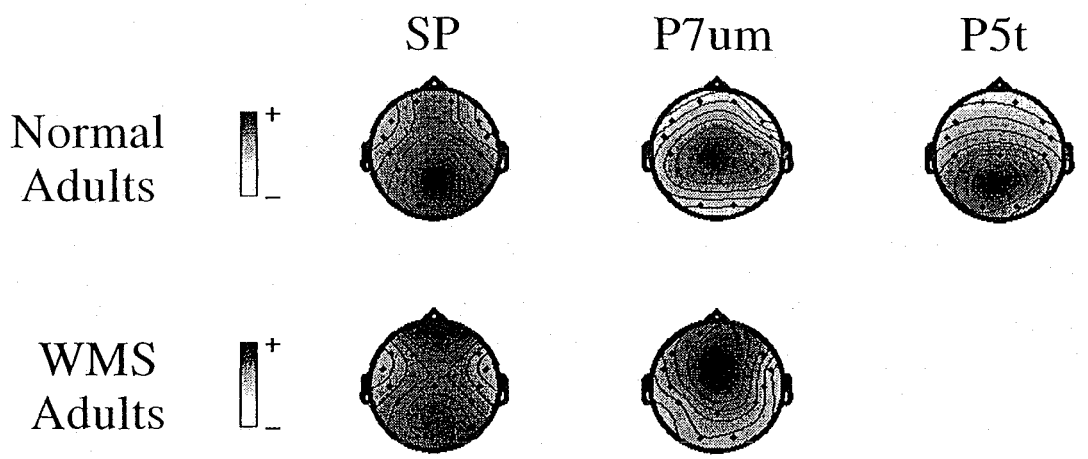

Figure 5. Scalp maps of the independent components in normal adults (top row) and in WMS adults (bottom row). Topographic maps are extrapolated from values at the electrode locations (shown as black dots). Two components in the same column have the same name because they are functionally analogous (are active in the same experimental conditions). Notice that the WMS components are more anterior than their controls counterparts.

analysis techniques. In a traditional ERP analysis of two groups' responses to face stimuli, Mills et al. identified a single late positive component, called P500, comprising all of the late wave data. By performing ICA on the data, we determined that the P500 in this task was not unitary, but rather was composed of two (in the WMS group) or three (in the controls group) spatially fixed, functionally distinct independent components.

5.1 The P500 match-mismatch effect

In the original study, Mills et al. found a P500 match-mismatch effect that was present in normal adults but not in WMS adults. Now that we have decomposed the P500 into its component parts, we can decompose the match-mismatch effect into *its* component parts. The P500 match-mismatch effect refers to the observation that the mean area of the response to mismatched targets was larger than the response to matched targets, but only for inverted targets, and only for the normal adults.

The difference in size between the responses to mismatched and matched targets can be explained by the P5t. Figure 3 demonstrates the larger activation of the P5t (envelope filled in dark gray) in the two mismatched targets conditions than in the two matched targets conditions. However, the P5t alone is not enough to explain the P500 match-mismatch effect. The P500 match-mismatch effect was only observed for inverted targets, but the P5t difference between matched and mismatched targets is present for both inverted and upright target conditions.

The missing piece of the puzzle is the P7um. Figure 3 shows the envelope of the P7um (filled in light gray) overlaid on the envelope of the P5t (filled in dark gray) for all four targets conditions. The activation of the P7um in the upright matched targets condition compensates for the smaller activation of the P5t, causing there to be no significant difference between the upright matched and upright mismatched targets conditions.

In the Mills et al. study, the P500 match-mismatch effect in normal adults was viewed as evidence that normal adults employ different brain systems in the recognition of upright faces than they use in the recognition of inverted faces. Having decomposed the P500 match-mismatch effect into a combination of the P5t and the P7um, we realize that only the P7um indexes the significant difference observed between upright and inverted face processing.

In the Mills et al. study, the lack of a P500 match-mismatch effect in WMS adults was viewed as substantiating evidence that unlike normal adults, WMS adults employ the same brain systems in the recognition of upright and inverted faces. By using ICA to decompose the late positive component for WMS adults, however, we found a P7um component whose activation is larger in response to upright matched targets than in all other stimulus conditions.

We can conclude that WMS adults *do* exhibit an electrophysiological difference in the way they recognize upright and inverted faces, which suggests that different brain systems may be involved in upright and inverted face recognition in WMS adults. Furthermore, the late-wave ERP difference between upright and inverted face processing that we observe in adults with Williams Syndrome is functionally analogous to the late-wave difference between upright and inverted face processing that we observe in normal adults.

In addition to their implications for understanding face processing in WMS adults, our findings raise important questions about face processing in normal children. Based on data similar to those that we analyzed, ERP studies of face processing in normal adolescents have concluded that children use the same brain systems to process upright and inverted faces [1]. Using ICA, we found evidence that WMS adults use distinct brain systems for upright and inverted face processing. Perhaps the ERPs of face processing in normal children are concealing similar results.

5.2 Future work

We plan to use ICA to analyze single-trial ERPs [4] for at least one of the WMS subjects. This may enable us to separate the ERP into components that are stimulus-locked (time-locked to stimulus onset) and components that are response-locked (time-locked to the button press). Some of these components may identify activity that is time-locked but not phase-locked to stimulus events—activity that is generally lost in averaging.

Acknowledgments

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