DYNAMICS OF COGNITIVE CONTROL AND MIDLINE THETA ACTIVITY ACROSS MULTIPLE TIMESCALES

AN ABSTRACT

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BY

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Abstract

Humans frequently encounter cognitive conflict situations, such as the need to ignore distractions or make a decision with multiple options. Cognitive control over attention and behavior in conflict situations is a basic executive functioning skill vital for goal-oriented behaviors. Musicians spend many hours exercising cognitive control while ignoring distractions, focusing on specific sounds, and avoiding incorrect movements. Therefore, musicians are a useful population to examine the effects of long-term experience on cognitive control. The current study used independent component analysis, time-frequency analysis, and ERP analysis on electrophysiological data to identify neocortical activity and timescales of cognitive control during an auditory Simon Task. Musicians showed no cognitive control advantage over non-musicians. Consistent with previous research, we found short-term compatibility sequence effects as well as longer-term effects of base rate (proportion of compatible trials) in response time Simon effect data. Sequence effects and a base rate x compatibility interaction also emerged for some ERP and ERSP components, including frontal theta in the ERSPs. We then used predictive models to test whether changes in the Simon effect across base rates were due to changing numbers of each sequence type that necessarily accompany base rate manipulations. Results indicate that sequence effects account for 17% of the reaction time cognitive control shift associated with proportion compatible manipulations. The base rate manipulation affected behavior and neural correlates above and beyond sequence effects.
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Introduction

Executive functions are a set of cognitive skills vital for intelligent behavior. They include the abilities to focus attention, remember instructions, plan, problem-solve, and inhibit impulses (Diamond, 2013) and rely on a dorsolateral prefrontal cortex circuit (Cieslik, Mueller, Eickhoff, Langner, & Eickhoff, 2015; Kane & Engle, 2002). One crucial executive function is cognitive control of conflict, which we use when we attempt to ignore distractions or choose between alternatives. Some distractions help us survive by forcibly capturing attention, such as an alarm warning of danger. Other distractions do not help with survival and would be better off ignored, such as a ticking clock in an office. Dealing with these forms of basic cognitive conflicts allows humans to flexibly respond to useful stimuli in the environment while ignoring unhelpful information.

Simon, Stroop, and Flanker tasks in different ways index cognitive control of conflict by testing the degree to which different types of information not needed to do a task nonetheless impairs performance, and these tasks have been used in numerous studies (Kornblum, Stevens, Whipple, & Requin, 1999; Tillman & Wiens, 2011). The classic Stroop Task has conflicting and irrelevant lexical information (Stroop, 1935). A Flanker task has distracting visual noise, typically with conflicting directional information (Eriksen & Eriksen, 1974). The Simon Task indexes the degree to which distracting spatial information captures attention (Simon & Rudell, 1967).
The current researchers used an auditory Simon Task because of the powerful abilities of auditory stimuli and space to capture attention and the large effects associated with the task. For example, the auditory system automatically detects the direction of new sounds, which alert us to dangers outside of our visual field (Hartmann, 1999; Scharf, 1998). The effects reported for auditory Simon tasks have also typically been larger than those reported for visual conflict tasks (e.g. Leuthold & Schröter, 2006; Vu, Proctor, & Urcuioli, 2003; Wascher, et al., 2001). Participants in this study listened to two amplitude modulated (AM) white noise sounds presented laterally, with each AM rate assigned to a lateralized response button (left/right) (See Figure 1). Participants were instructed to ignore sound location and respond based solely on AM rate. The Simon effect occurs when reaction times are faster with matching (compatible) vs. conflicting (incompatible) stimulus/response button laterality (Simon & Rudell, 1967).

Cognitive control uses central and prefrontal brain areas (Cieslik et al., 2015). For example, Kerns (2006, 2004) found greater fMRI activation in the anterior cingulate cortex for incompatible than compatible Simon or Stroop Task trials. Previous research has also implicated prefrontal brain regions in cognitive control using time-frequency analysis on EEG data (e.g. Cohen & Cavanagh, 2011; Cohen & Ridderinkhof, 2013). Time-frequency analysis, also known as the event-related spectral perturbation (ERSP), provides a measure of power - relative to a baseline - of the oscillations in cortical electrical activity across frequency bands and time (Le Van Quyen & Bragin, 2007). Increases in power following a stimulus indicate synchronized cortical cell activity in response to the stimulus (Nunez & Srinivasan, 2006; Pfurtscheller & Lopes da Silva, 1999).
Theta (4-8 Hz) power in prefrontal brain areas increases during cognitive control and response conflict (Cavanagh & Frank, 2014; Cohen & Cavanagh, 2011). Theta in the hippocampus and frontal midline areas has also been previously linked to contextual effects in episodic memory (Hsieh & Ranganath, 2014). The current study looked at frontal midline theta during cognitive control in an auditory Simon task and in relation to contextual effects on cognitive control during the task. Specifically, we examined frontal midline theta adjustments on a trial-to-trial basis as well as in response to overall conflict proportion during the task.

**Base Rate Effects**

Cognitive control is context-dependent and adapts to the task at hand. Beyond effects of whether an individual task trial introduces conflict or not, shifts in cognitive control have been examined across many trials in minutes-long conflict task blocks. Overall conflict amount across a task block spanning minutes can be manipulated by varying the proportion, or base rate, of compatible trials, incompatible trials, and (sometimes) neutral trials (e.g. Tzelgov, et al., 1992). Base rate changes cause shifts in cognitive control of conflict, such that the effect of conflict increases as the base rate of compatible trials increases (Logan & Zbrodoff, 1979; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Tillman & Wiens, 2011; West & Bailey, 2012). For example, West and Bailey (2012) found a larger reaction time Stroop effect for blocks that were 75% compatible than blocks that were 25% compatible.

Base rate has also been associated with conflict processing in event-related potential (ERP) research using electroencephalographic (EEG) data. The medial frontal
negativity (MFN) is a negative peak in electrical activity at frontal electrode sites 250 to 350 ms after presentation of an acoustic Simon Task stimulus (Sur & Golob, 2014) or around 450 ms (known as the “N450”) after a visual Stroop task stimulus (Tillman & Wiens, 2011; West & Bailey, 2012). The MFN is larger for incompatible than compatible trials, and this difference increases as the base rate of compatible trials increases. Because the MFN occurs pre-response, it is likely related to conflict detection and processing. A later ERP component, called the frontal slow wave, occurs over prefrontal brain areas several hundred milliseconds after conflict task stimulus presentation and is also sensitive to trial type and base rate (e.g. West & Bailey, 2012). Because it occurs around or after the average response, the frontal slow wave may reflect between-trial working memory capacity updates, response processing, or processing of previous trial demands.

When looking at behavioral and ERP responses across entire task blocks (often several minutes), more frequent conflict trials reduce overall conflict effects. Effects of base rate are often discussed as changes in cognitive control strategy across an entire block (e.g. Risko, Blais, Stolz, & Besner, 2008). This effect may occur because more frequent incompatible trials may serve as reminders to filter out conflict, thus improving performance in base rates with frequent conflict trials. Participants may also detect rates of each trial type and adjust their cognitive control intensity accordingly, with adjustments spanning task blocks lasting minutes.

*Sequence Effects*

Adjustments in cognitive control of conflict have also been examined on short, trial-to-trial timescales (on the order of seconds). The Simon Effect is smaller following
incompatible trials than compatible trials (Egner, 2007; Gratton, Coles, & Donchin, 1992; Wühr & Ansorge, 2005), and reaction time on the current trial is also faster when it repeats the previous trial type than when the trial type switches (Egner, 2007). Similar effects have been found for frontal and parietal theta ERSPs during visual Simon and Stroop tasks, such that the difference between compatible and incompatible trials was larger following compatible trials than incompatible trials (Gulbinaite, van Rijn, & Cohen, 2014; Tang, Hu, & Chen, 2013). Thus, behavioral and neural measures of cognitive control adjust dynamically on short timescales throughout conflict tasks.

Sequence effects versus base rate

Two-trial sequences compose whole task blocks, so short-term sequence effects at least partially overlap with whole-block base rate effects on the timescale of minutes. For example, in a 75% compatible base rate, most trials are preceded by a compatible trial. Since trials following a compatible trial display a larger Simon Effect than those following an incompatible trial, sequence effects would cause the 75% base rate to have a larger overall Simon Effect than lower base rates. Thus, base rate effects must be at least partially driven by sequence effects. However, most researchers describe base rate effects on minutes-long timescales without mentioning overlapping sequence effects. An exception is Risko et al. (2008), who found that controlling for effects of whether Simon task stimulus and response locations completely repeated, partially repeated, or completely alternated from trial to trial reduced the effect of base rate by 47%. Thus, at least some of the base rate effect on longer time scales is driven by sequence effects on short time scales.
The current study had two main purposes. First, we wanted to define the impact of manipulating the base rate of compatible trials on cortical potentials (ERPs and ERSPs) identified using independent component analysis (ICA). We hypothesized that a subset of the independent components would be strongly modulated by base rate, and would likely reflect frontal and parietal areas previously associated with conflict control. The second objective was to determine if the components modulated by base rate reflected a genuine effect of the base rate context. The alternative hypothesis was that the base rate effects were due to sequence effects that covaried with base rate. These two possibilities were distinguished by using the ICA results from the 50% base rate, when compatible and incompatible trials were equally likely to examine sequence effects. Quantitative modeling was then used to predict base rate effects in the 25% and 75% compatible conditions solely from sequence effects in the 50% base rate. Rejection of these models would imply context-based adjustments in cognitive control across minutes-long timescales in addition to trial-by-trial adjustments evident as sequence effects.

Musical Experience

Musical performance engages many cognitive processes, such as interplay among perception and action, short and long-term memory, and cognitive control of conflict. For example, musicians exercise cognitive control when they ignore a distraction while playing. The current project examined whether the development of musical skills is associated with improvement of higher order cognitive control, which in turn may be useful in other aspects of daily life. Despite showing benefits in a variety of contexts such as cognitive aging, neural rehabilitation, and academic outcomes (e.g. Hanna-Pladdy & MacKay, 2011; “Harmony Project 2014 Annual Report,” 2014; Schlaug, Marchina, &
Norton, 2008), little research has been done on the effects of playing music or singing on specific aspects of daily life cognition.

The small body of research on music and cognition is promising. Researchers have found an association between musical experience and IQ (Schellenberg, 2005) and musical experience and reasoning abilities (Forgeard, Winner, Norton, & Schlaug, 2008). Aging research has uncovered benefits of musical training on executive functions (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007). In another study, low-income children who received musical training were more likely to develop age-appropriate literacy skills than a control group who did not receive musical training (Slater et al., 2014).

Music programs and executive functioning are also both associated with broad life outcomes in non-musical domains. For example, the Harmony Project, which teaches music to low income children in Los Angeles, cites parent-reports of improved grades, behavior, and mood in over 80 percent of students (“Harmony Project 2014 Annual Report,” 2014). Also associated with classroom success is executive functioning (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009).

Researchers have suggested that enriching cognitive experiences contribute to the development of executive functioning (working memory capacity, inhibition, cognitive control) and that a lack of cognitive stimulation is one reason why low socioeconomic status is associated with lower executive functioning (Hackman & Farah, 2009). Cognitive psychologists have debated for decades whether or not cognitive skills can transfer between domains (e.g. Handbook of Educational Psychology, 1996). Some studies have found that skills learned in one domain do not transfer to other domains. For example, Sims & Mayer (2002) found that spatial skills associated with playing a Tetris
videogame were limited to improved ability to rotate tetris or tetris-like shapes, without
improvements on other spatial skills. Some improvements may only be capable of “near
transfer” or transfer to very similar skills. Near transfer occurs for musical training with
respect to fine motor skills (e.g. Costa-Giomi, 2005) and auditory or melodic
discrimination (Morrongiello & Roes, 1990). However, researchers do not yet know
whether improvements associated with musical training also transfer to domains outside
of perception and action. Research by Bialystok & DePape (2009) found faster overall
performance during a Stroop task in musicians compared to non-musicians, as well as a
smaller Stroop effect in musicians compared to non-musicians. Research has not yet
examined effects of conflict amounts or neural differences associated with inhibition in
relation to musicianship. The current project assessed the relationship between musical
experience and cognitive control using the auditory Simon Task.

Methods

Subjects

Fifty-seven subjects were recruited from Tulane’s undergraduate psychology courses
in exchange for extra credit (mean age = 20.1 ± 2.5 years, 19 males, 2 left-handed, 24 ≥ 3
years of musical experience). None reported a history of major neurological or
psychiatric disorders. Hearing thresholds in all subjects were within the normal range, as
verified with audiometric testing. A subset of subjects (n=35) completed cognitive tests
and surveys including two working memory capacity tests (Reading Span; Listening
span) (Daneman & Carpenter, 1980; Unsworth, et al., 2005) and a questionnaire about
musical experience. All subjects were given a handedness questionnaire (Oldfield, 1971).
Ten subjects were excluded from analysis due to technical issues, hairstyles that
prevented EEG recording, and excessive EEG artifacts. A total of 47 subjects were included in the results below.

**Design**

Factors of current trial type (compatible vs. incompatible), base rate (25%, 50%, 75% compatible), and previous trial type were used to examine current trial type x base rate and current trial type x previous trial type interactions. We expected an interaction such that trial type effects would increase as the base rate of compatible trials increased. The 50% base rate had equal proportions of compatible and incompatible trials, as well as equal proportions of each possible N-1 trial sequence. Thus, participants could gather no information about which trial type was most likely to occur during this condition. By making predictive models based on sequence effects in the 50% base rate condition, we were able to compare whether short-timescale sequence effects fully predicted changes in the Simon effect across 25% and 75% base rates or whether cognitive control was also adjusted based on contextual information across the longer timescale of task blocks. Factors of musician and non-musician, grouped by a median split, were analyzed with respect to the above cognitive control effects during the Simon task. We expected better cognitive control for musicians than non-musicians, evidenced as a smaller behavioral Simon effect for musicians. We also expected that musicians’ experience detecting sequence of sounds would contribute to a greater change in Simon effect across base rates for musicians than non-musicians.

**Simon Task**
Participants were familiarized with two monaural white noise sounds (100-10,000 Hz, 200 ms duration, ~65 dB nHL, 5 ms rise/fall) that had one of two amplitude modulation rates (25 or 75 Hz, 90% depth). Subjects pressed one of two buttons with their left/right hand to indicate AM rate (counterbalanced across subjects). The sounds were presented every 2.0 seconds to the left or right ear with insert headphones. For “compatible” trials the sound’s location matched the side of its button assignment (ex. right ear, right hand response). For “incompatible” trials, the AM rate specified a response by the hand opposite the ear that received the sound (ex. right ear, left hand response). To test for effects of base rate, every participant received blocks with three different base rates of compatible trials (25%, 50%, and 75%). Each participant received three blocks of each base rate with 161 trials in each block for a total of nine blocks. The first trial in each block was not analyzed. The order of base rates was approximately counterbalanced across subjects. A practice block with 40 trials was given before testing.

**Electrophysiological Recordings**

Electroencephalography (EEG) was recorded using a 64-channel Ag/AgCl electrode cap positioned in accordance with the 10/20 system (Compumedics Neuroscan, Charlotte, NC). Recording followed standard EEG data collection methods in our lab (Starr & Golob, 2006; Yurgil & Golob, 2013). The cap had a reference electrode between CZ and CPZ, as well as four additional electrodes placed above and below the left eye and near the lateral corners of each eye to track eye movements. Recording during the Simon Task took place inside a sound attenuating, electrically shielded booth (IAC Acoustics, Bronx, New York). EEG data was digitized at 500Hz with a DC-100Hz band-pass filter and
recorded using Curry 7 Neuroimaging Suite Software (Compumedics Neuroscan, Charlotte, NC).

Data Analysis

EEG Processing. EEG data was processed offline using the EEGLAB (Delorme & Makeig, 2004) plugin for Matlab (The Mathworks, Inc., Natick, MA). Continuous EEG data files were high-pass filtered at 1Hz, resampled at 250 Hz, epoched from -800 to 1200 ms around stimulus onset, and re-referenced to the average. Channels containing lots of noise in the recording, EKG, or frequent non-stereotyped artifacts as well as epochs with non-stereotyped artifacts such as muscle activity were removed. Epochs were coded for factors of current Simon Task trial type (compatible vs. incompatible), previous trial type (compatible vs. incompatible), and base rate (25%, 50%, or 75% compatible). ERPs were low-pass filtered at 30Hz to reduce noise.

Independent Component Analysis. We used independent component analysis (ICA) to reduce noise in the EEG data and reduce confounding due to volume conduction. Individual signals within the brain mix together via volume conduction, resulting in mixed signals from multiple brain sources recorded at the scalp (Nunez & Srinivasan, 2006). Based on differences in timing and voltage at EEG electrodes, ICA identifies physiologically or functionally separate sources of electrical activity recorded at the scalp (Delorme & Makeig, 2004). ICA can also identify muscular and ocular artifacts in the EEG recording (Delorme, Sejnowski, & Makeig, 2007). Extended infomax ICA was used to identify independent components (ICs) within the EEG data (Bell & Sejnowski, 1995). Components were deemed consistent with brain activity when they had scalp map
distributions that were smooth across channels, log-function shaped spectral power curves with peaks at frequency bands that reflect brain activity (θ, α, β), and/or consistent ERP peaks across task trials. Components made up of eye movements, facial muscle activity, EKG, or noise in the recording were not included in subsequent analysis.

Dipoles for each IC were modeled with the DIPFIT2 plug-in from the FIELDTRIP toolbox for MATLAB (Oostenveld, et al., 2011; http://www.ru.nl/neuroimaging/fieldtrip). A boundary element model (BEM) was used to represent skin, skull, and cortex using the Montreal Neurological Institute (MNI) canonical brain template. Time-frequency analysis was calculated for each independent component to show average changes in event-related spectral power over time and across a range of frequencies. These calculations were done by convolving stimulus-locked single-trial data with Morlet wavelets to get time-frequency power. At the lowest frequency (4Hz) three cycles were used. Results were visualized as color heat maps representing power in decibels (dB) along time and frequency axes. For the purpose of running ANOVA statistics, results were quantified as average power over time-frequency windows of interest.

Cluster Analysis. Principal component cluster analysis using EEGLAB’s k-means algorithm was used to group physiologically and functionally similar independent components from different subjects. In order to ensure that biologically similar components were clustered together, component dipole location was weighted three times as heavily as the scalp map, ERP, and ERSP. Clustering was performed several times using k=8 to k=14 k-means and an outlier cluster with component centroids > 3 standard
deviations from cluster centroids. Eight clusters were observed to have relative stability and contain most subjects across increasing values of k (See Figure 3). In some cases, a subject contributed more than one independent component to a cluster. Because varying numbers of contributions to clusters would cause individual subjects to be weighted unequally in statistical analyses, one component per subject per cluster was selected based on quality of the component measures (ERP, ERSP, scalp map, dipole location). The clusters showed the same ERP and ERSP effects before and after pruning when visualized in EEGLAB with a false discovery rate correction for multiple comparisons.

**Statistical Analysis**

Only trials with correct behavioral responses were analyzed. Median trial reaction times and electrophysiological measures for each condition were used for each subject to reduce the influence of outliers. Some follow-up ANOVAs violated the sphericity assumption, so Greenhouse-Geisser corrected p-values are reported when applicable.

**Base Rate and Sequence Effects.** We tested for trial type x base rate and previous trial type x current trial type (sequence effects) interactions during the Simon task for reaction time, accuracy, and electrophysiological measures (ERPs and ERSPs) for each cluster of interest. For ERPs and ERSPs, interaction statistics for clusters were first graphed in EEGLAB using a false discovery rate statistical correction for multiple comparisons. These plots were used to select windows with significant predicted effects. Window averages were computed and analyzed using repeated-measures ANOVAs conducted in R (R Foundation for Statistical Computing, 2015). The base rate x trial type interaction was analyzed using 2 x 3 repeated-measures ANOVAs with factors of Simon Task trial type (compatible vs. incompatible) and Simon Task base rate (25%, 50%, 75%
compatible). A 2 x 2 repeated measures ANOVA with factors of current trial type (compatible vs. incompatible) and previous trial type (compatible vs. incompatible) tested sequence effects in the 50% compatible condition. Follow-up comparisons across base rates were made within each trial type following a significant trial type x base rate interaction, with a Bonferroni corrected alpha level of 0.025. Compatible vs. incompatible comparisons within each level of previous trial type were also made upon finding significant sequence effects, with a Bonferroni corrected alpha level of 0.025.

**Base Rate vs. Sequence Effects (Table 1).** We made quantitative models predicting the Simon effect in each base rate from sequence effects in the 50% compatible condition. Sequence effects were only examined in the 50% base rate, because the 25% and 75% base rates had too few trials of the least frequent N-1 sequence to analyze the EEG data. The average reaction time for each sequence type (compatible-compatible, compatible-incompatible, incompatible-compatible, incompatible-incompatible) was applied to each base rate, weighted based on the percentage of each sequence type in the base rate. The base rate of compatible trials was expected to attenuate the Simon Effect above and beyond sequence effects, such that more frequent compatible trials increased the Simon Effect while more frequent incompatible trials decreased the Simon Effect. We then used the ordinary least squares regression slope fitting procedure to get each subject’s observed and predicted change in Simon effect across base rates. We tested the predicted versus observed slopes using paired-sample t-tests to see whether context (base rate) attenuated the Simon effect across the timescale of minutes above and beyond trial-to-trial adjustments on the timescale of seconds.
Musical Experience. A smaller Simon effect was expected for musicians than non-musicians and was tested as a musicianship (musician vs. nonmusician) x trial type interaction for reaction time. A significant musicianship x trial type x base rate repeated-measures ANOVA was also expected. These interactions were also analyzed for percent accuracy and midline frontal and central cluster ERP and ERSP windows associated with cognitive control.

Results

Behavior (Figure 2)

Overall: Reaction time and accuracy were separately examined using 2 (trial type) x 3 (base rate) ANOVA tests. For reaction time there was a main effect of trial type (F(1,46) = 164.6, p<.001), with incompatible trials being slower than compatible trials. There was also a main effect of base rate because responses slowed as base rate increased (F(2,92) = 4.54, p<.05). These effects were qualified by a significant trial type x base rate interaction, indicating progressive increases in the size of the Simon Effect as the base rate of compatible trials increased (F(2,92) = 69.5, p<.001). Follow-up ANOVAs for each trial type showed that compatible trial reaction times were slowest when compatible base rate was highest (F(2, 92) = 10.14, p<001). For incompatible trials reaction time was slowest when compatible trial base rate was lowest (F(2, 92) = 12.26, p<.001).

Incompatible trials were significantly less accurate than compatible trials (F(1,46) = 81.12, p<.001), and accuracy decreased as compatible base rate increased (F(2,92) = 32.06, p<.001). These main effects were qualified by a significant trial type x base rate interaction, showing that the accuracy differences between compatible and incompatible trial accuracy increased as the percentage of compatible trials increased (F(2,92) = 48.47,
Separate analysis of each trial type showed that as the compatible trial base rate increased accuracy on compatible trials increased slightly ($F_{(2, 92)} = 4.75, p < .025$), while for incompatible trials accuracy decreased ($F_{(2, 92)} = 46.80, p < .001$).

Sequence Effects: Sequence effects in the 50% base rate condition were tested using a 2 (previous trial type) x 2 (current trial type) repeated measures ANOVA test. For reaction time there was an interaction of previous trial type x current trial type ($F_{(1, 46)} = 171.24, p < .001$). Post hoc tests showed a significant Simon effect only when the previous trial was compatible ($t_{(46)} = 16.39, p < .001$) and not following incompatible trials (See Figure 2b).

Analysis of accuracy also showed a significant previous trial type x current trial type ($F_{(1, 46)} = 26.84, p < .001$). Post-hoc comparisons found a significant difference between compatible and incompatible trials following compatible trials ($t_{(46)} = 6.19, p < .001$), and a smaller, but still significant, difference following incompatible trials, ($t_{(46)} = 3.58, p < .001$) (See Figure 2b).

**Independent Component Analysis**

Analyses focused on the two midline clusters. These were chosen for in-depth analysis because the measures (ERPs, ERSPs) showed a conflict effect during the Simon task, and the topographic plots suggest sources in in frontal/parietal areas implicated in cognitive control (See Figure 3). These clusters were also extremely consistent across individuals, as the vast majority of subjects (42 & 45 out of 47) contributed to each of these two clusters. Time windows of interest showing trial type x base rate effects and/or
sequence effects were visually identified for cluster ERPs, and time-frequency windows of interest were identified for ERSPs.

**Midline frontal cluster compatibility x base rate (Figure 4a).** A 2 (trial type) x 3 (base rate) repeated-measures ANOVA for the ERP averaged from 400-500 ms revealed greater negativity for compatible than incompatible trials ($F_{(1,41)} = 10.41, p<.01$) and no significant interaction. In the grand average ERPs, incompatible trials appeared to have a later slow wave onset than compatible trials, but individual subjects had too much variability in the slow wave to select peaks and analyze latency effects.

ERSP power increased in the theta and alpha bands (4-12 Hz) between 300-500 ms after stimulus onset. Theta and alpha were analyzed together because this effect appeared consistent across 4-12 Hz. Incompatible trials had significantly higher power than compatible trials ($F_{(1,41)} = 53.07, p<.001$), and this main effect was qualified by a significant 2 (trial type) x 3 (base rate) interaction ($F_{(2,82)} = 20.76, p<.001$). Follow-up ANOVA tests on each trial type showed that compatible trial power did not significantly differ across base rates, whereas power for incompatible trials increased as base rate increased, ($F_{(2,82)} = 21.04$, Greenhouse-Geisser corrected $p<.001$).

**Midline frontal cluster sequence effects (Figure 4b).** A 2 (current trial type) x 2 (previous trial type) ANOVA testing sequence effects on slow wave ERP amplitudes in the 400-500 ms time window was significant ($F_{(1,41)} = 6.91, p=.012$). Mirroring the behavioral results, the Simon effect was present after compatible trials ($t_{(41)} = 3.07, p<.01$), while a Simon effect was not evident after incompatible trials.

A 2 (current trial type) x 2 (previous trial type) ANOVA testing sequence effects in the 300-500 ms 4-12 Hz ERSP window was also significant ($F_{(1,41)} = 25.93, p<.001$).
Similar to behavioral effects and ERP effects for this cluster, post-hoc comparisons revealed no significant effect of trial type following incompatible trials. Following compatible trials, ERSP power for incompatible trials was significantly larger than compatible trials ($t_{(41)} = 6.92, p<.001$).

**Central cluster compatibility x base rate (Figure 5a).** The main effect of trial type was significant for the slow wave ERP in the central cluster 400-700 ms time window, showing greater negativity for incompatible than compatible trials ($F_{(1,44)} = 16.12, p<.001$). This effect was qualified by a significant trial type x base rate interaction showing a larger Simon Effect as the percentage of compatible trials increased ($F_{(2,88)} = 16.41, p<.001$). Post-hoc ANOVAs showed that ERP amplitude for compatible trials did not significantly differ across base rates. However, amplitude became significantly more negative across base rates for incompatible trials ($F_{(2,88)} = 7.08, p<.01$).

A similar interaction was also present for ERSPs in the central cluster. Theta (4-8 Hz) and alpha (8-12 Hz) power increased primarily in the 300-600 ms and 300-500 ms time range, respectively. For theta power (300-600 ms) main effects of trial type ($F_{(1,44)} = 37.42, p<.001$) and base rate ($F_{(2,88)} = 3.57, p<.05$) were present, and were qualified by a significant 2 (trial type) x 3 (base rate) interaction ($F_{(2,88)} = 13.7, p<.001$). The difference between compatible and incompatible trials progressively increased as the percentage of compatible trials increased (See Figure 4). Post-hoc ANOVAs showed no difference in compatible trials across base rate, while incompatible trial power increased as base rate increased, ($F_{(2,88)} = 12.33, p<.001$).

In the 300-500 ms alpha time-frequency window, a 2 (trial type) x 3 (base rate) ANOVA on ERSP power was also significant ($F_{(2,88)} = 6.65, p<.01$), in addition to a main
effect of trial type showing higher power for incompatible than compatible trials ($F_{(1,44)} = 4.42, p<.05$). As with theta, the difference between compatible and incompatible trials progressively increased as compatible trials became more common. Within each level of trial type, power did not differ significantly across base rates.

**Central cluster sequence effects (Figure 5b).** A 2 x 2 repeated-measures ANOVA testing sequence effects on ERP amplitude in the 400-700 ms time window was not significant ($p = .084$). The trend was toward a larger Simon effect following compatible than incompatible trials.

A 2 x 2 repeated-measures ANOVA testing sequence effects was significant for ERSP power in the 300-600 ms theta time-frequency window ($F_{(1,44)} = 13.38, p<.001$). The difference between compatible and incompatible trials was significant following compatible trials ($t_{(44)} = 5.21, p<.001$) but not following incompatible trials.

Alpha ERSPs (300-500ms window) showed a significant 2 (previous trial type) x 2 (current trial type) repeated-measures ANOVA ($F_{(1,44)} = 4.25, p = .043$). Post-hoc tests revealed that the Simon effect was present following compatible trials ($t_{(44)} = 2.58, p<.025$) but not incompatible trials.

**Predictive Models**

**Behavioral Predictive Models (Figure 6a).** For comparison of predicted vs. observed data the slopes of the dependent variables (reaction time, accuracy, ICA measures) were calculated as a function of base rate. The predicted slopes were derived from the results in the 50% base rate conditions. For behavioral data the slope directions were extremely consistent across subjects. For example, 46 out of 47 subjects had a
positive reaction time Simon effect slope across base rates. For reaction time and percent accuracy, base rate attenuated the Simon effect above and beyond the effect predicted from sequence effects in the 50% condition. A paired-sample t-test indicated that the observed reaction time Simon effect slope across base rates was significantly steeper than the slope predicted from our quantitative models ($t_{(46)} = 4.65, p<.001$), with the Simon effect increasing across base rates. For percent accuracy the observed Simon effect slope across base rates was also steeper than the predicted slope ($t_{(46)} = -6.88, p<.001$). The $r^2$ values for the correlations between predicted and observed values indicated that sequence effects accounted for 16.6% of the variance in the observed slope of the reaction time Simon effect and 35.6% of the variance for the accuracy Simon effect.

**Midline frontal cluster ERPs (Figure 6b).** Unlike behavioral results, there was no significant difference in the slopes of observed versus predicted Simon effect for ERPs in the 400-500 ms time window. Thus, for the midline frontal cluster ERPs sequence effects accounted for the observed results across base rates.

**Midline frontal cluster ERSPs (Figure 6c).** A model predicting the 300-500ms 4-12 Hz ERSP Simon effect slope from sequence effects under-predicted the Simon effect slope across base rates. A paired-sample t-test indicated that the observed Simon effect slope across base rates was steeper than quantitatively modeled predicted (paired-sample $t_{(41)} = 3.15, p<.01$). The $r^2$ value for the correlation between predicted and observed Simon effect slopes for this measure indicated that sequence effects accounted for 8.0% of the observed change across base rates.

**Central cluster ERPs (Figure 6b).** Sequence effects in the 50% base rate under-predicted the Simon effect slope across base rates for central cluster ERPs in the 400-700
ms time window (paired-sample $t_{(44)} = -3.94, p < .001$). The difference between trial types got larger as base rate of compatible trials increased. The $r^2$ value for the correlation between predicted and observed Simon effect slopes for this measure indicated that sequence effects accounted for 22.1% of the observed change across base rates.

Central cluster ERSPs (Figure 6c). The Simon effect slope across base rates for ERSP power in the 300-600 ms 4-8 Hz (theta) time-frequency range was greater for our observed versus predicted data (paired-sample $t_{(44)} = 2.5, p = 0.02$). The $r^2$ value for the correlation between predicted and observed Simon effect slopes for this measure indicated that sequence effects accounted for 13.7% of the observed change across base rates. The Simon effect slope across base rates was also larger than predicted for ERSP power in the 300-500 ms 8-12 Hz (alpha) time-frequency range (paired-sample $t_{(44)} = 2.15, p < .05$). The $r^2$ value for the correlation between predicted and observed Simon effect slopes for this measure indicated that sequence effects accounted for 1.9% of the observed change across base rates. The Simon effect increased as the base rate of compatible trials increased with a steeper slope for observed than predicted data.

Musical Experience

We hypothesized that the attentional demands of playing an instrument would confer an advantage to musicians in the Simon task, for both behavioral and EEG-based measures. Instead, musicians showed no significant advantage on Simon task performance compared to non-musicians (See Figure 7), and the musicianship x trial type x base rate interaction was also non significant for behavioral and ICA measures. On average, musicians were faster than non-musicians, but this difference only approached
statistical significance ($t_{(46)} = 1.73, p = .09$). To check whether our median split was appropriate and for a possible non-linear trend, musical experience in years was also plotted against the Simon effect as a continuous variable. No trends were visible between musicianship and behavioral or ICA measures of cognitive control.

**Discussion**

The main findings of this study are that independent components associated with conflict have effects at both longer (minutes) and shorter (seconds) timescales. The Simon effect was context-dependent on the timescale of minutes-long task blocks, and progressively increased as the base rate of incompatible trials decreased. These effects were present for behavioral and neural measures, including frontal and central theta band ERSPs previously associated with cognitive control. Quantitative modeling was used to determine how much of the contextual effects on minutes-long timescales could be predicted from short-term sequence effects. For behavior and some ICA components, the effects at longer timescales were not fully accounted for by effects at shorter timescales. Here we discuss the significance of the new findings with respect to contextual effects on cortical activity related to cognitive control.

*Behavioral results and implications for contextual effects*

As with previous studies, the Simon effect increased in tandem with the base rate of compatible trials (e.g. Logan & Zbrodoff, 1979; West & Bailey, 2012). In principle sequence effects could fully account for the influence of base rate on the Simon effect, as the two variables covary. Instead, our modeling based on sequence effects in the 50% condition found that in the 25% and 75% base rate conditions sequence effects only
accounted for 16.6% of variance in reaction time and 35.6% of the variance in accuracy (See Figure 5). Using somewhat different methodology that focused on sequence effects of stimulus and response locations, Risko et al. (2008) found that sequence effects accounted for 47% of the behavioral Simon Effect for 25, 50, and 75% compatible base rates. Hommel et al.’s feature integration account (2004) suggests that stimulus and response location sequences affect conflict task performance and are the underlying reason for observed compatibility sequence effects. Stimulus and response location does encode some congruency/compatibility information. For example, if stimulus and response locations completely repeat or alternate, the resulting consecutive trials must either be both compatible or both incompatible. However, Jiang et al (2014) developed a Bayesian model of cognitive control trained to predict cognitive control from base rate effects and congruency sequence effects. They found that the model predicted conflict task performance when it incorporated base rate and congruency sequence information – and that stimulus and response location patterns did not improve model fit. Taken together, the above studies all show an effect of base rate on cognitive control at a longer timescale than trial-by-trial sequence effects. However, whether stimulus response location sequence effects and compatibility sequence effects completely overlap is not fully clear. A conflict effect may be smaller following an incompatible trial due to recent conflict and activation of a conflict processing system. Conflict effects may also decrease following an incompatible trial because an incompatible-incompatible sequence would not involve a change in stimulus-response location pairs.

The Simon effect for reaction time, which is a measure of differences between trial types, had a strong linear increase across base rates. However, when trial types were
examined individually both trial types had a nonlinear relation to base rate (cf. Figures 2a vs. 6a). For both trial types, encountering a trial type with greater than 50% frequency did not yield reaction time advantages for that trial type, while encountering a trial type less than 50% slowed reaction time compared to the other base rates. For example, even though incompatible trial performance improved as this trial type went from 25% to 50% of the total trials, going from 50% to 75% conflict trials did not yield a performance advantage. Previous studies on base rate have often used only two base rates, (e.g. West & Alain, 2000), and we have not seen this exact non-linear pattern discussed in other studies. In contrast, accuracy the increase in the Simon Effect across base rates was mostly driven by a decreased accuracy for incompatible trials as the compatible base rate increased, which fit in with West & Bailey’s Stroop task findings (2012). These patterns may each map onto different cortical responses. Similar to accuracy, frontal midline ERSP responses, central ERPs, and central theta ERSPs changed more for incompatible than compatible trials across base rates.

**Independent components and frontal theta**

Both the midline frontal and central ICA clusters had significant increases in frontal theta power during incompatible versus compatible trials, which is consistent with previous research implicating frontal theta in cognitive control (Cavanagh & Frank, 2014; Cohen & Cavanagh, 2011; Tang et al., 2013). Event-related synchronization and the Simon effect were also present in the alpha band (8-12 Hz) in midline frontal and central areas. This fits in with previous research suggesting that alpha oscillations are related to aspects of attentional control such as inhibitory control and timing (Klimesch, 2012).
Further, our finding of frontal midline theta during cognitive control fits in with emerging literature suggesting that this brain area coordinates with a larger neural network to perform executive functions (e.g. Clayton, Yeung, & Cohen Kadosh, 2015; von Stein & Sarnthein, 2000). The average increase we observed in theta and alpha power occurred before and during the average Simon Task response time. This time course suggests that theta plays a role throughout conflict detection as well as during response preparation and execution. However, event-related synchronization during a temporal window must be calculated using time before and after each ERSP data point, thus limiting its temporal precision. Therefore, the conclusions we can draw about the temporal relationships between the ERSP timing and more precise measures such as response time are somewhat broad. A future study might examine ERSP correlations between the prefrontal cortex and other brain areas to further assess how the prefrontal cortex coordinates with other brain areas during cognitive control.

Our study’s finding of changes in theta across base rates suggests that frontal theta is sensitive to context on base rate timescale of minutes and/or sequence effects on the timescale of seconds that covary with base rate. Frontal theta power increases were seen for incompatible trials as they became more infrequent. Thus, cortical neurons increase their synchronization more at these frequencies when handling rare conflict than frequent conflict. Theta associated with cognitive control appears to be more consistent when conflict is frequent and adjust more in response to individual stimuli types when incompatible trials are rare. This pattern fits in with behavioral results and the Dual Mechanisms of Control model suggesting contextual adjustments in cognitive control on different timescales (e.g. Braver, 2012). This effect could occur if it is more efficient to
continuously filter out irrelevant information across longer timescales when it is common, and evaluate the need for cognitive control on a short, trial-by-trial basis when incompatible trials are rare.

*Independent component analysis and ERPs*

The relationship between the midline frontal component’s ERP and previous studies of the MFN/N450, which were recorded from the scalp but not defined using ICA, was unclear. The issue is that although both occur at about the same time range and have similar topographies (e.g. Bailey, West, & Anderson, 2010; Tillman & Wiens, 2011; West & Bailey, 2012), our midfrontal component had greater negativity for compatible vs. incompatible trials, while the MFN/N450 has the opposite pattern. Previous studies that discuss an ERP N450 or medial frontal negativity around this timeframe during conflict tasks and also use an average reference show greater negativity for incompatible than compatible trials at frontal electrode sites (Bailey et al., 2010; Tillman & Wiens, 2011; West & Bailey, 2012). When the scalp data at the channel level were examined before performing ICA there was an effect consistent with the N450/MFN seen in previous studies. However, the midfrontal cluster identified with ICA had an effect in the opposite direction, with greater negativity for compatible than incompatible trials. The N100, a negative ERP peak following auditory stimuli, was present in the expected direction in both the channel and the midfrontal ICA component. Therefore, this effect is not due to inverted ICA scalp projections, which can be ambiguous in polarity following ICA (Hyvärinen, Karhunen, & Oja, 2004). Visual inspection suggests that this ERP component started later for incompatible than compatible trials, and that this latency
effect may have led to a greater negativity for compatible trials before the component fully peaked for incompatible trials. However, we are not completely sure why the direction of this effect is reversed compared to our pre-ICA channel data and other studies using channel analysis.

**Quantitative modeling**

With the exception of midline frontal ERPs, which did not show significant base rate x trial type effects, all of our observed behavioral and neural measures showed greater Simon effect attenuation across base rates than predicted from sequence effects. Thus, context across the timescale of minutes caused adjustments in cognitive control above and beyond covarying adjustments on a trial-to-trial basis spanning timescales of seconds. This result further supports a Dual Mechanisms of Control model in which stimulus-driven reactive control occurs on a trial-by-trial basis while proactive control intensity increases or decreases based on contexts across entire task blocks. It is also consistent with Jiang, et al’s (2014) empirical data and Bayesian model of flexible cognitive control on short and long timescales. Our slope-fitting procedure for observed and predicted data revealed effects in a consistent direction for most subjects on all measures. Thus, sequence effects tended to reliably covary with base rate effects for individual subjects. One potential drawback of fitting a slope to the observed data and then comparing to the predicted data is that this method would not have worked had the Simon effect not progressively increased across base rates in a linear pattern.

*Comparison of neural and behavioral findings*
Although most of our neural measures showed increasing Simon effects across base rates like behavioral responses did, they had different patterns for individual trial types than reaction time. For behavior, both compatible and incompatible trials showed performance improvements as they became more common. For most neural measures examined in this study, including midline frontal cluster 4-12 Hz ERSPs, central cluster ERPs, and central cluster theta ERSPs, only incompatible trials changed significantly across base rate. This pattern suggests that the ability to filter out irrelevant spatial information is dependent on conflict probability, and that non-conflict trial performance is not as dependent on probabilities. A future study could potentially use single-trial ERSP analysis, similar to Cohen & Cavanagh, (2011), to further examine how frontal theta maps onto behavioral performance in different contexts.

*Musical Experience*

We hypothesized that musical experience, which involves a rich set of cognitive skills, would be associated with better cognitive control. We failed to find an association between musical experience and cognitive control or its neural correlates. Previous research has shown near transfer for some skills associated with learning to play music (e.g. Costa-Giomi, 2005), as well as positive academic outcomes associated with musical training (e.g. “Harmony Project 2014 Annual Report,” 2014). However, some studies have failed to find cognitive improvements associated with musical training (Mehr, Schachner, Katz, & Spelke, 2013). Others have found mixed results on executive function tasks in musicians versus non-musicians, such as better auditory but not better visual attention for musicians (Strait, Kraus, Parbery-Clark, & Ashley, 2010). Although the Simon task involves responding to auditory stimuli and exercising a cognitive skill
involved in playing music, it may not be similar enough to playing an instrument for skills gained with musical experience to transfer. It is also possible that improvement in outcomes associated with music programs, such as better mood and academic achievement, could be due to mechanisms other than cognitive control. For instance, music instructors may provide social support and a safe environment. Further research is needed to determine through which mechanisms musical training results in improved academic and other outcomes.

Conclusions

Given that behavior and frontal theta adjust on minutes-long and seconds-long timescales, and that adjustments on shorter timescales do not fully predict effects at longer timescales, we conclude that cognitive control adjusts on timescales of minutes depending on context. Our results indicate a dynamic system that adapts to the task at hand across multiple timescales. Frontal and central brain areas support dynamic attention changes from second-to-second, and the same areas are also sensitive to the broader context of goal-oriented behaviors.
References


Mehr, S. A., Schachner, A., Katz, R. C., & Spelke, E. S. (2013). Two randomized trials provide no consistent evidence for nonmusical cognitive benefits of brief preschool


Table 1

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<th>Base Rate</th>
<th>25% Compatible</th>
<th>75% Compatible</th>
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<td>Incompatible (IC)</td>
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<tr>
<td>Sequence Type</td>
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**Predictive Model Calculations**

M = Mean, P = Predicted Response

C-C = Compatible- compatible, IC-C = Compatible- incompatible

IC-IC = Incompatible- incompatible, C-IC = Incompatible- compatible

**25% Compatible**

\[
.25(M_{50\%C-C}) + .75(M_{50\%IC-C}) = P_C
\]

\[
.25(M_{50\%C-IC}) + .75(M_{50\%IC-IC}) = P_{IC}
\]

\[
P_{SimonEffect} = P_{IC} - P_C
\]

**75% Compatible**

\[
.75(M_{50\%C-C}) + .25(M_{50\%IC-C}) = P_C
\]

\[
.75(M_{50\%C-IC}) + .25(M_{50\%IC-IC}) = P_{IC}
\]

\[
P_{SimonEffect} = P_{IC} - P_C
\]
Figure 1. Illustration of left Simon task trials

Left button

Sound assigned to left button

Left Compatible Trial

Left Incompatible Trial

Right button

Sound assigned to right button
Figure 2. Behavioral effects

**a. Reaction time**

Compatibility vs. Base Rate

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<td>75</td>
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Sequence Effects

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<th>Incompatible</th>
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</thead>
<tbody>
<tr>
<td>Previous Trial</td>
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**b. Percent accuracy**

Compatibility vs. Base Rate

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Sequence Effects

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<tbody>
<tr>
<td>Previous Trial</td>
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Figure 3. Clustering results

a. Component clusters

1. Midline Frontal Cluster
2. Central Cluster

b. Clusters of interest

1. Midline Frontal Cluster
   Grand Average ERPs

2. Central Cluster
Figure 4. Midline frontal cluster

a. Trial type x base rate effects

ERPs

400-500 ms ERP windows

4-12 Hz 300-500 ms ERSP windows

Power in dB

Microvolts

Base Rate
b. Sequence effects

![Graph showing sequence effects](image)

- Compatible
- Incompatible

Previous Trial Compatible
Previous Trial Incompatible

![ERP windows graph](image)

400-500 ms ERP windows

<table>
<thead>
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<th>Previous Trial</th>
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<tbody>
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4-12 Hz 300-500 ms ERSP windows

<table>
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<tbody>
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![Power in dB graph](image)

<table>
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<th>Previous Trial</th>
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<tbody>
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Figure 5. Central cluster effects

a. Trial type x base rate effects

ERPs

- Compatible
- Incompatible

25%C 50%C 75%C

0 200 400 ms

-0.75 -1.25

Base Rate

Interaction p-value

0 0.1 0.01 0.001

Time (ms.)

Compatible Incompatible

Power in dB

250-500 Hz

500-700 Hz

300-500 ms alpha ERSP

b. Sequence effects

Previous Trial Compatible Previous Trial Incompatible

400-700 ms ERP windows

Microvolts

25 50 75

Base Rate

Interaction p-value

2.8 -2.8

Time (ms.)

Compatible Incompatible

Power in dB

300-600 ms theta ERSP

300-500 ms alpha ERSP

0.3 0.4 0.5 0.6

Microvolts

300-500 ms alpha ERSP

Current Trial

Compatible Incompatible

Hint: The provided text does not include all the content visible in the image, particularly the bar charts and bar graphs. The full context and details of the figures would require the full image content.
Figure 6. Predictive Simon effect models

a. Behavior

Reaction Time

Accuracy

Predicted Simon effect
Observed

Base Rate

b. ERPs

Frontal midline 400-500 ms

Central 400-700 ms

Frontal midline alpha-theta 300-500 ms

Central theta 300-600 ms

Central alpha 300-500 ms

Base Rate

Base Rate

Base Rate

43
Figure 7. Musical Experience

Trial Type x Musical Experience for Reaction Time

Musical Experience vs. Reaction Time Simon Effect
Biography

Lisa Chinn received her Bachelor of Science in Psychology from the University of Oregon in 2009. She then assisted with research on youth access to alcohol at Oregon Research Institute and ADHD Oregon Health and Science University. In 2013, she began doctoral studies in Psychological Science at Tulane University with a focus in cognitive neuroscience. At Tulane she has been awarded the Southern Regional Education Board doctoral fellowship and a summer Flowerree fellowship.