A NEAR INFRARED SPECTROSCOPY STUDY OF COUNTERFACTUAL THINKING

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CHAPTER I

INTRODUCTION

We are not only able to think about things that are happening in the present or remember things that have happened in the past, but we are also capable of performing mental simulation. This amazing capacity of the human mind refers to the ability to imagine things that may happen in the future and things that might have happened in the past. One kind of mental simulation – counterfactual thinking – has been a focus of psychological research ever since Kahneman and Tversky's (Kahneman & Tversky, 1982) seminal chapter on the simulation heuristic.

Counterfactual thinking refers to the imagination of scenarios that are contrary to fact. Here we will define counterfactual thoughts as past conditional thoughts in which the antecedent is false. Suppose that yesterday you were in a traffic jam on the way to a meeting and arrived late. Subsequently you might have had the following counterfactual thought: 'If I had left earlier I would have arrived on time.' Although the consequent is also false in this example (you actually were late), in another counterfactual thought the consequent might not be undone (i.e. be true). For example, you might think "Even if I had left earlier I still would have been late."

The first example above is an example of an upward counterfactual thought. In these types of counterfactual thoughts reality is compared to an alternative that is better than reality. Counterfactual thoughts have been shown to occur spontaneously following negative affect (Sanna & Turley, 1996), and these spontaneous counterfactual thoughts are more frequently upward counterfactuals (Roese & Olson, 1997). Upward counterfactual thinking has been described as functional, since it helps people avoid mistakes in the future that have occurred in the past (Roese, 1997). According to Roese, upward counterfactual thoughts also increase negative affect, such as regret, in the short term. Here we have decided to focus on upward, rather than downward counterfactual thoughts, since we are interested in studying the properties of the types of counterfactual thinking that have been shown to occur spontaneously (Roese, 1997) .

The neural correlates of counterfactual thinking have not yet been examined. However, a number of recent studies provide evidence linking counterfactual thinking to the prefrontal cortex. Knight & Grabowecky (Knight & Grabowecky, 1995) describe the case of a man who had damage to his dorsolateral prefrontal cortex who appeared to have deficits in counterfactual thinking. He neither expressed counterfactuals nor expressed counterfactual emotions, such as grief and regret.

Impairments in counterfactual thinking have been shown to be related to schizophrenia (Hooker, Roese, & Park, 2000), which is a disorder involving many cognitive deficits related to the prefrontal cortex, such as working memory deficits (Lee & Park, 2005; Perlstein, Dixit, Carter, Noll, & Cohen, 2003) and executive functioning deficits (Pantelis et al., 1997). Hooker and colleagues showed that individuals with schizophrenia generated less spontaneous counterfactual thoughts and had worse performance on the counterfactual inference test (C.I.T.), a multiple choice measure of counterfactual thinking, than normal controls.

Similar results have been observed in Parkinson's disease (McNamara, Durso, Brown, & Lynch, 2003). Individuals with Parkinson's disease also generated less spontaneous counterfactual thoughts and did worse on the C.I.T. than normal controls. In addition, McNamara and colleagues showed that performance on these two measures of counterfactual thinking was positively correlated with performance on two tests associated with frontal lobe functioning (the Stroop and Tower of London tasks).

It is unclear whether counterfactual thinking is more related to activity in the dorsolateral prefrontal cortex or the orbitofrontal cortex. Beldarrain and colleagues (Beldarrain, Garcia-Monco, Astigarraga, Gonzalez, & Grafman, 2005) showed that individuals with prefrontal cortex lesions had impaired spontaneous counterfactual generation, but not impaired performance on the C.I.T. These deficits in counterfactual thinking did not differ with respect to lesion location (whether the lesion was in orbitofrontal cortex or dorsolateral prefrontal cortex).

Individuals with lesions to the orbitofrontal cortex have been shown to experience less regret than normal controls after losing on a gambling task (Camille, Coricelli, Sallet, Pradat-Diehl, & Sirigu, 2004), and regret has been linked to upward counterfactual thinking (Zeelenberg & van Dijk, 2005). Increased levels of regret following losses on a gambling task have also been correlated with increased activity in the medial orbitofrontal region as measured by fMRI (Coricelli et al., 2005).

Since the prefrontal cortex has been shown to be important in regret and counterfactual thinking, we decided to look at the neural correlates of counterfactual thinking in the frontal cortex. In this study, we utilized Near Infrared Spectroscopy (NIRS), a noninvasive neuroimaging method that utilizes near infrared light, to examine hemodynamic activity associated with a counterfactual thinking task compared to a control task, which relied on causal thinking. NIRS allows one to measure changes in levels of oxyhemoglobin (oxyHb), deoxyhemoglobin (deoxyHb), and total hemoglobin (totalHb) in the outer layers of the cerebral cortex. It thus provides information not directly available from functional Magnetic Resonance Imaging (fMRI), since fMRI is only sensitive to changes in deoxyHb. The regions we looked at included the dorsolateral prefrontal cortex but not the orbitofrontal cortex. We could not acquire images of the orbitofrontal cortex with NIRS because NIRS probes cannot be placed above this region, as that would entail placing the probes over the subjects' eyes.

We hypothesized that counterfactual thinking would be associated with higher maximum percent changes of oxyHb and totalHb and lower minimum percent changes of deoxyHb than causal thinking in the frontal cortex, since it is likely that counterfactual thinking requires larger cognitive resources that rely on the frontal cortex, such as working memory (Miller & Cohen, 2001). People generally keep two possibilities in mind to understand counterfactual conditionals, but only one to understand factual conditionals (Walsh & Byrne, 2005). Thus, it is likely that counterfactual thinking requires a larger load on working memory than non-counterfactual causal thinking.

CHAPTER II

METHODS

Twelve right-handed healthy individuals (six males and six females, with a mean age of 36.1 years (SD = 9.1) and a mean educational level of 15.7 years (SD = 1.8)) participated in this study. Individuals with a history of substance abuse, head injury, mental illness, or neurological disorder were excluded.

Participants were given the WASI to measure full scale I.Q. (Mean = 104.5 (SD = 12.4), the schizotypal personality questionnaire (SPQ) to measure schizotypal personality (Mean = 16.8 (SD = 10.6)), the PANAS to measure positive and negative affect (Mean PA = 30.5 (SD = 6.0), Mean NA = 16.4 (SD = 7.4)), and letter number sequencing to measure verbal working memory capacity (Mean Total Number Correct = 15.8 (SD = 4.6), Mean letter number sequencing span = 6 (SD = .7)). In addition, participants were given a packet that contained the C.I.T., six logical thinking questions, and free response questions.

The C.I.T. is a four question multiple choice measure that examines an individual's ability to think counterfactually. For each item, two similar negative events for two different individuals are given followed by three response options. This measure is based on research showing that counterfactual thinking is heightened by outcomes preceded by unusual, rather than typical actions, and also by events that almost occur (Roese, 1997). The correct response for each item on the C.I.T. is the response that corresponds with one of these two factors shown to heighten counterfactual thinking.

Further information about this task, including the items and responses is given in Hooker *et al.* (2000).

Each logical thinking question contained three sentences. The first sentence described a logical premise (e.g. “all ice is hot”) and the second sentence described a situation (e.g. “Ann has some ice.)” The third sentence was a question that related the first two sentences to each other (e.g. “Is it cold?”). Participants had to answer whether the third sentence was true, given the facts in the first two sentences.

Each free response item described a story that was likely to elicit counterfactual thoughts in the reader. After reading each story, participants wrote down any thoughts that came to mind. The instructions for this task and one of the stories are listed in Table 1. We recorded the total number of counterfactual ideas participants wrote down for all four stories.

Table 1. Free response task

Instructions: Please read each story below. After each one, write whatever thoughts come to mind.
1) Nick eats dinner at the same restaurant nearly every night. One night he decided to try a new restaurant. Nick got food poisoning that night.

Imaging Task

Each participant underwent NIRS scanning while completing four blocks of an imaging task. Each block contained 40 pairs of stimulus and response sentences; with 10 pairs of sentences in each of four conditions (Counterfactual Realistic (CfR), Counterfactual Unrealistic (CfU), Causal Realistic (CsR), and Causal Unrealistic (CsU)).

For all conditions, a stimulus sentence was shown on the screen for 3500 milliseconds. This sentence described a negative event in the first person tense (e.g. "I spilled coffee on my pants"). Stimulus sentences were in the first person tense and had a negative valence so that they would easily elicit upward counterfactual thoughts when they were followed by the response sentence in the CfR condition. The stimulus sentence was directly followed by another sentence (response sentence) which was on the screen for 5500 milliseconds.

For all four conditions, participants decided whether or not they agreed with the response sentence by pressing a key with their right hand. Participants were instructed to respond as quickly and as accurately as possible. A diagram of the task is shown in Figure 1.

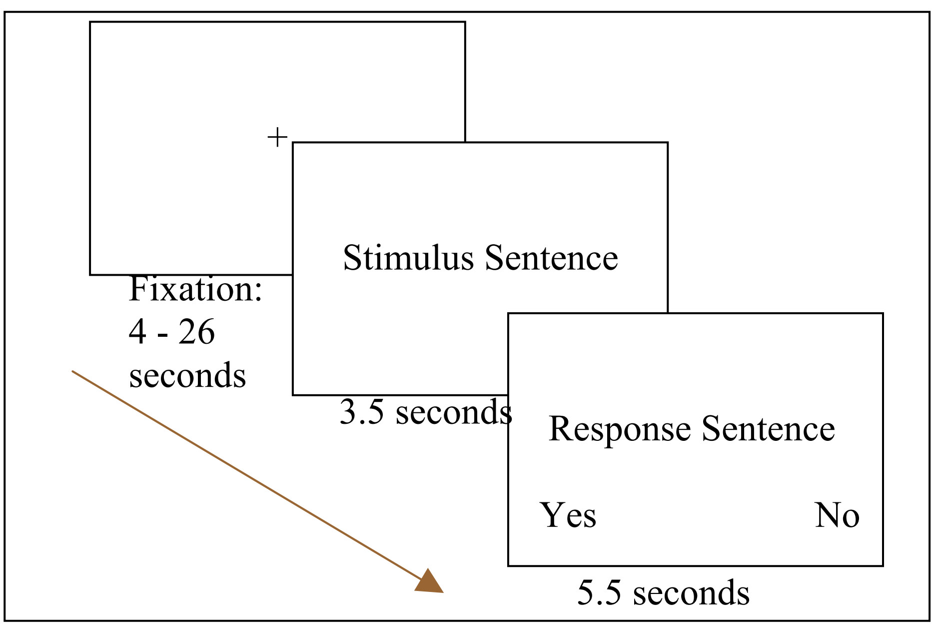


Figure 1. Diagram of one trial in the imaging task.

For the counterfactual conditions, the second sentence described an action they should have done differently in the past. For the CfR condition, the response sentence described an action that could have prevented the negative event in the stimulus sentence. It was compatible with an upward counterfactual thought, and thus was realistic, since people tend to spontaneously generate upward counterfactuals after negative events. For the CfU condition, the response sentence described an action that would not have prevented the event, and may in fact have made it worse. This condition was unrealistic, because people do not tend to spontaneously generate these types of counterfactuals after negative events. Since the response sentence in the counterfactual conditions described something that may or may not have prevented the negative event, performing it required participants to think counterfactually about the event.

For the causal conditions, the response sentence depicted something that either did (CsR) or did not follow (CsU) logically from the information in the stimulus sentence. The outcomes described in the CsR condition were realistic, while those described in the CsU condition were not.

The correct response for realistic items was yes (agree) while that for unrealistic items was no (disagree). An example of a sentence from each condition is shown in Table 2.

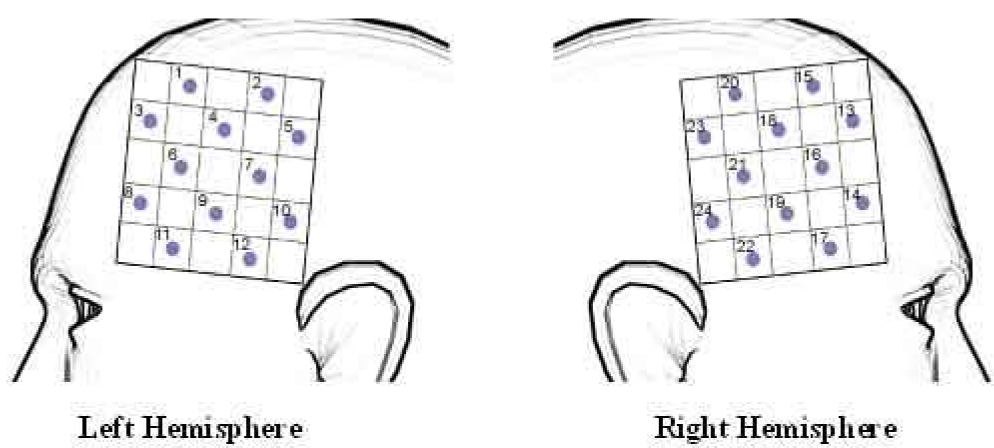
A causal thinking task was used as a control task, because it was postulated that while both causal thinking and counterfactual thinking require logical thinking, counterfactual thinking requires something additional: the ability to mentally simulate an alternative that did not occur. We used both realistic and unrealistic conditions of counterfactual and causal tasks to see if the cognitive and neural properties underlying counterfactual thinking relied on whether the thinking was realistic (i.e. whether it was specific for upward counterfactuals).

Table 2. Stimuli from each condition

Condition	Stimulus Sentence	Response Sentence
Counterfactual Realistic (CfR)	I spilled coffee on my pants.	I should have drank more carefully.
Counterfactual Unrealistic (CfU)	I spilled coffee on my pants.	I should have drank less carefully.
Causal Realistic (CsR)	I spilled coffee on my pants.	After that, my pants were wetter.
Causal Unrealistic (CsU)	I spilled coffee on my pants.	After that, my pants were drier.

An event related design was utilized. Stimulus-response sentence pairs from all four conditions were randomized within each block. The stimulus sentences used in each block were the same; however the exact response sentences paired with each stimulus sentence were different in each block, such that each stimulus sentence was paired once with a response sentence in each of the four conditions. The order of blocks was counterbalanced across participants. After each response sentence, subjects were instructed to look at a fixation cross; this intertrial interval ranged between 4 and 26 seconds and was randomized across trials. We randomly jittered the intertrial intervals to increase efficiency and so that we could extract the hemodynamic time courses associated with the tasks. An exponential distribution of intertrial intervals was used to maximize efficiency.

The NIRS apparatus used was a Hitachi ETG 4000. Signals for changes in oxyHb, deoxyHb, and totalHb in μmol/mml were acquired at a sample rate of 10 Hz from anterior regions in each hemisphere. We utilized a 690-830 spectrometer composed of emitter-detector pairs. One three by three probe set containing 12 data channels was placed over the frontal cortex in each hemisphere (see Figure 2 for locations of probe sets and channels).



Note: Blue dots indicate the channels that were measured.
Each channel is listed with a different number.

Figure 2. Location of NIRS probe sets.

Landmarks used for probe placement were the top of the eyebrows (the bottom of the probe set was placed directly above the top edge of the eyebrow) and the top part of the most anterior connection of the ears to the skull (the bottom corner of the probe set was placed on the skull next to this connection). The path length for adults was 3 cm. The detected signals were converted to chromophore concentrations by using the modified Beer-Lambert Law. High and low pass filters and linear trend removal were applied to the data. We extracted signal time courses on a channel by channel basis for the four conditions of the imaging task from deconvolution plots that had been corrected for serial correlations. This data was deconvolved from the onset time of the response trials.

CHAPTER III

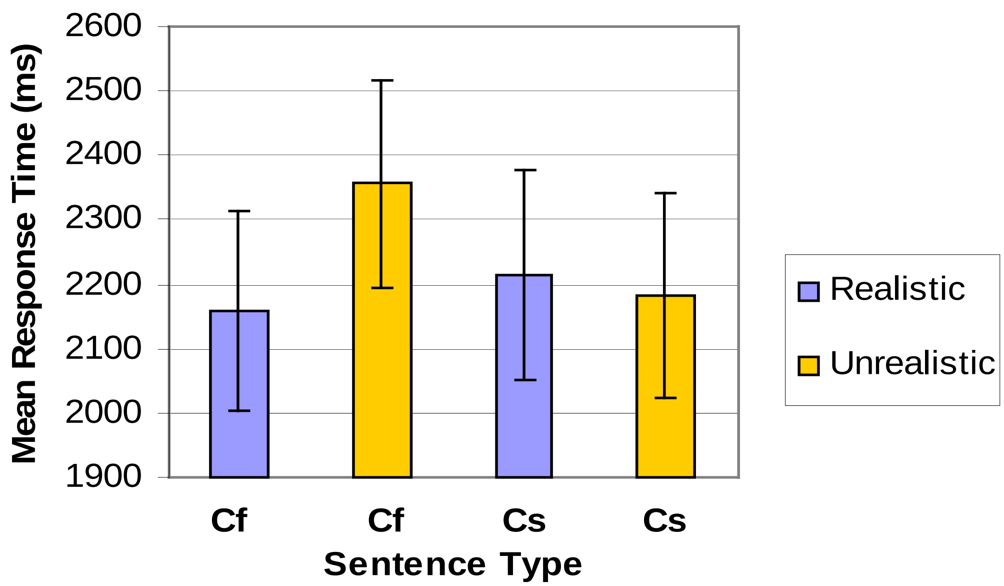
RESULTS

The mean score for participants on the C.I.T. was 1.7 out of 4 items correct (SD = 1.2). On the logical thinking task, participants answered on average 5.3 out of 6 items correctly (SD = 1.2). For the free response questions, on average participants wrote down 1.4 counterfactual ideas for all four stories (SD = 2.1). After correcting for multiple comparisons, there were no significant correlations between any of these variables and any of the other participant characteristics described in the Methods section. In addition, none of the other participant characteristics correlated significantly with each other.

Imaging Task - Behavioral Data

A repeated measures ANOVA of the effects of sentence type (counterfactual or causal) and realism (realistic or unrealistic) on the average number of items answered correctly was performed. Participants answered an equal number of counterfactual and causal items correctly ($F(1, 11) = .22$, $p = .65$). They also answered an equal number of realistic and unrealistic items correctly ($F(1, 11) = 1.31$, $p = .28$). Furthermore, there was not a significant interaction of sentence type by realism ($F(1, 11) = .02$, $p = .89$).

Another repeated measures ANOVA was performed on the effects of sentence type and realism on response time for correct trials. Response time for counterfactual and causal trials was equivalent ($F(1, 11) = 3.12$, $p = .11$). The response time for realistic and unrealistic trials was also equivalent ($F(1, 11) = 4.20$, $p = .07$). However, there was a significant interaction of sentence type by realism ($F(1, 11) = 18.08$, $p = .001$) on response time. For counterfactual trials, participants responded more quickly for the realistic trials; however they responded at a similar speed for both types of causal trials (See Figure 3). Pairwise comparisons showed that participants responded significantly faster for CfR than CfU trials ($t(11) = -5.46$, $p < .001$) and significantly faster for CsU than CfU trials ($t(11) = 4.54$, $p < .001$).



Note: Bars indicate standard errors.

Figure 3. Graph of Mean Response Time for correct trials as a function of sentence type (counterfactual (Cf) and causal (Cs)) and realism.

The means and standard deviations of the average number correct and the average response time for correct trials are listed in Table 3. None of these variables correlated significantly with any of the other participant characteristics. Furthermore, none of the response time variables correlated significantly with any of the accuracy variables.

Table 3. Means and Standard Deviations for Total Number Correct and Response Time for Correct Trials for each condition

	Mean	SD
CfR Total Correct	9.79	0.26
CfU Total Correct	9.67	0.29
CsR Total Correct	9.75	0.38
CsU Total Correct	9.65	0.25
CfR Response Time (ms)	2157.05	536.22
CfU Response Time (ms)	2355.69	554.42
CsR Response Time (ms)	2214.94	568.24
CsU Response Time (ms)	2181.55	552.15

Note: Maximum Total Correct is 10

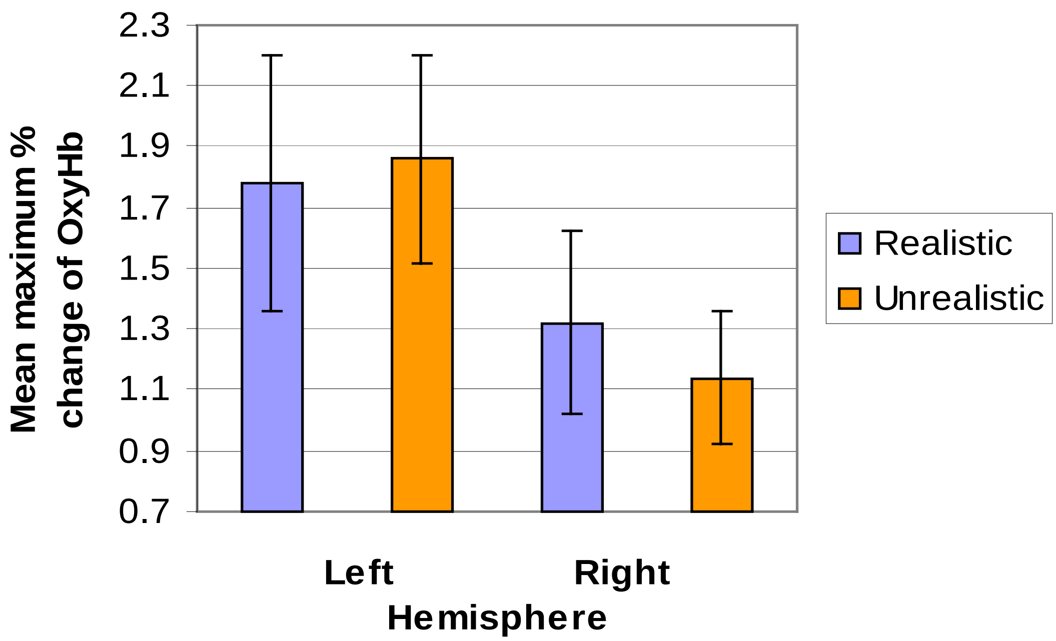
We only analyzed correct responses because of the infrequency of incorrect and null (unanswered) response trials. Participants answered 97.14% of all items correctly.

Imaging Data

For all analyses on oxyHb and totalHb, we compared the maximum percent change in hemoglobin levels that occurred between 5 and 12 seconds after the onset of the response sentences of correct trials. We performed similar comparisons for deoxyHb levels, except that we compared the minimum percent change, rather than the maximum percent change, that occurred between 5 to 12 seconds after the onset of the response sentences of correct trials. We chose to analyze these points of change, because NIRS studies have shown that neuronal activation generally leads to increases in oxyHb and totalHb, and decreases in deoxyHb (Sakatani, Katayama, Yamamoto, & Suzuki, 1999).

Repeated measures ANOVAs of hemisphere by channel by sentence type by realism on changes of oxyHb, totalHb, and deoxyHb levels were performed. We found significantly greater percent change maximums of oxyHb in the left hemisphere than in the right hemisphere ($F(1, 11) = 4.9$, $p = .049$). There also was a significant interaction of hemisphere by realism on maximum percent changes of oxyHb ($F(1, 11) = 11.34$, $p = .006$). Figure 4 shows that in the left hemisphere there were lower maximum percent changes of oxyHb for realistic than unrealistic trials, while in the right hemisphere the maximum percent changes were higher for realistic than unrealistic trials. None of the comparisons of hemisphere by realism reached statistical significance. For totalHb and deoxyHb, none of the effects were significant.

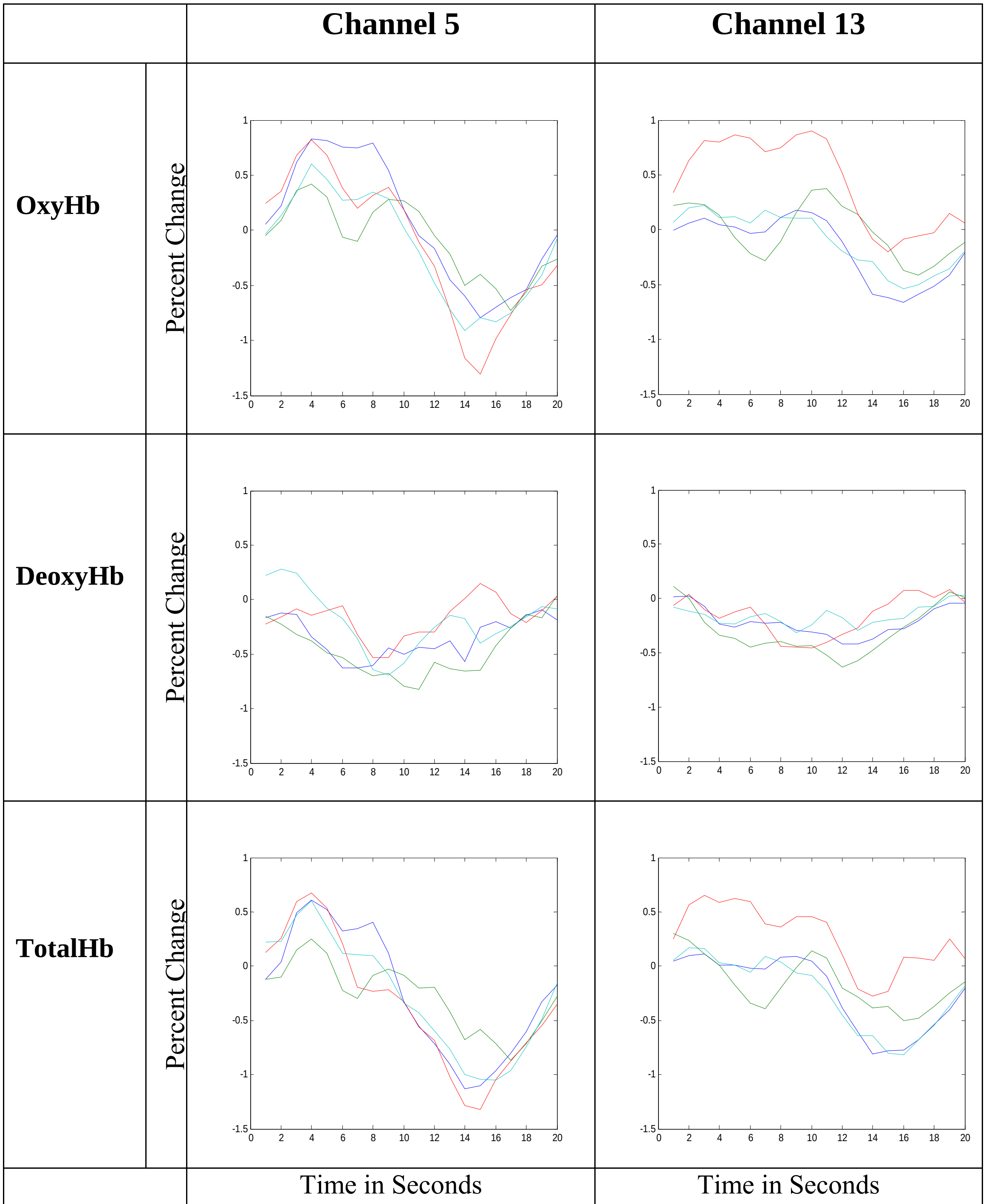
We also performed repeated measures ANOVAS for the effects of hemisphere by channel by sentence type by realism on time of maximum percent change (for oxyHb and totalHb) and minimum percent change (for deoxyHb). For oxyHb and totalHb, none of the factors affected the time of maximum percent change. However, for deoxyHb there was an effect of sentence type on time of minimum percent change ($F (1, 11) = 9.74$, $p = .01$), such that the time of minimum percent change for the counterfactual trials was later than that for the causal trials.



Note: Bars indicate standard errors.

Figure 4. Levels of mean maximum percent increases of oxyHb in the left and right hemisphere for realistic and unrealistic trials.

Time courses for percent change of oxyHb, deoxyHb, and totalHb associated with each of the four conditions are given for one channel in each hemisphere (channel 5 – left hemisphere, and channel 13 – right hemisphere) in Figure 5. The beta values on the y-axis of the plots represent percent signal change from baseline.



Key: Dark blue: CfR Red: CsR
Green: CfU Light Blue: CsU

Note: See Figure 2 for locations of Channels 5 and 13

Figure 5. Hemodynamic Time courses.

CfR and CsR conditions

To observe the neural correlates of realistic counterfactual thinking, we compared the levels of most extreme percent change in hemoglobin for the CfR and the CsR conditions. We postulated that any additional activity associated with the CfR condition over the CsR condition would be associated with realistic (upward) counterfactual thinking. Repeated measures ANOVAS of hemisphere by channel by condition were performed on oxyHb, totalHb, and deoxyHb. None of the effects were significant.

A paired comparison of the average number of correct counterfactual realistic and causal realistic items showed that participants answered an equivalent number of items correctly in both conditions ($t\ (11) = -1.24$, $p = .24$). Similarly, a paired comparison of the average response time for counterfactual realistic and causal realistic items showed that response time was also similar ($t\ (11) = .39$, $p = .70$).

CfU and CsU conditions

To observe the neural correlates of unrealistic counterfactual thinking we compared the levels of most extreme percent change in hemoglobin for the CfU and CsU conditions. We postulated that any additional activity associated with the CfU over the CsU condition would be associated with unrealistic counterfactual thinking. Repeated measures ANOVAS of hemisphere by channel by condition were performed on oxyHb, totalHb, and deoxyHb. There was a significant effect of hemisphere on maximum percent change of oxyHb; maximum percent changes of oxyHb were higher in the left hemisphere ($F\ (1, 11) = 6.00$, $p = .032$) than in the right hemisphere. There were no other significant effects for oxyHb, deoxyHb, and totalHb.

A paired comparison of the average number of correct counterfactual unrealistic and causal unrealistic items showed that participants answered an equivalent number of items correctly in both conditions ($t(11) = .233$, $p = .82$). As stated earlier in the paper, however, the response time for unrealistic counterfactual trials was slower than for unrealistic causal trials ($t(11) = 4.54$, $p = .001$).

CfR and CfU conditions

To observe the neural correlates of the realistic aspect of counterfactual thinking (the aspect associated specifically with upward counterfactual thoughts) we compared the levels of maximum percent change in hemoglobin for the CfR and CfU conditions. We postulated that any additional activity associated with the CfR over CfU condition would be associated with realism of counterfactuals. Repeated measures ANOVAS of hemisphere by channel by condition were performed on oxyHb, totalHb, and deoxyHb. There was a significant effect of hemisphere on maximum percent changes of oxyHb and totalHb. Levels of maximum percent changes of oxyHb and totalHb were higher in the left hemisphere (oxyHb: $F(1, 11) = 5.52$, $p = .039$; totalHb: $F(1, 11) = 6.52$, $p = .027$) than in the right hemisphere. There were no significant effects for deoxyHb.

A paired comparison of the average number of correct counterfactual realistic and counterfactual unrealistic items showed that participants answered an equivalent number of items correctly in both conditions ($t(11) = 1.07$, $p = .31$). As stated earlier in the paper, the response time for unrealistic counterfactual items was slower than that for realistic counterfactual items ($t(11) = -5.46$, $p < .001$).

CsR and CsU conditions

To observe the neural correlates associated specifically with the realistic aspect of causal thinking we compared the levels of most extreme percent change of hemoglobin for the CsR and CsU conditions. We postulated that any additional activity associated with the CsR over the CsU condition would be associated with realism (or correct logic). Repeated measures ANOVAS of hemisphere by channel by condition were performed on oxyHb, totalHb and deoxyHb. There were no significant effects for oxyHb, totalHb, and deoxyHb.

A paired comparison of the average number of correct causal realistic and causal unrealistic items showed that participants answered an equivalent number of items correctly in both conditions ($t(11) = .81$, $p = .44$). In addition, response time was similar for trials in both conditions ($t(1, 11) = .57$, $p = .58$).

We did not look at the effects of hemisphere, channel, and condition on time of most extreme percent change for any of the two condition comparisons. We decided not to do this because we were primarily interested in looking at the magnitude, rather than the timings, of the most extreme percent changes of hemoglobin.

CHAPTER IV

DISCUSSION

In the current study, we observed similar levels of most extreme percent change of hemoglobin in frontal cortex for both counterfactual and causal thinking. However, we also observed an effect of sentence type on the time of the minimum percent change of deoxyHb, such that the time of the minimum percent change of deoxyHb was later for the counterfactual than for the causal conditions.

Participant accuracy was not affected by sentence type or sentence realism. This may have been due to a ceiling effect in the task, since mean accuracy was over 95% for each condition. Response time for correct trials was significantly affected by the interaction of sentence type and realism. Multiple comparisons among the four conditions showed that response time for the CfU condition was significantly slower than that for the CfR and CsU conditions. The longer response time for the unrealistic counterfactual items could have been related to the later time of minimum percent change in deoxyHb levels for the counterfactual trials.

Our lack of activation and behavioral effects for counterfactual thinking may have been due to properties of the experimental task. For both the counterfactual and causal imaging tasks, participants read stimulus sentences that depicted negative scenarios. It is possible that participants automatically generated counterfactual thoughts after reading these stimulus sentences, because negative events often lead to spontaneous counterfactual thoughts. However this is unlikely, because before beginning this study, we gave lists of stimulus sentences to 12 individuals (not those who participated). Some of these sentences resembled those in the study while the other sentences were identical. Individuals were told to read each sentence and write down their thoughts. Although some individuals did write down counterfactual thoughts; the occurrence of counterfactual responses was uncommon, consisting of only 4% of the total responses.

A more likely possibility is that while counterfactual and causal thinking may rely on similar neural substrates in the areas of frontal cortex that we examined, they may show differences in other regions, such as the orbitofrontal cortex. This is entirely possible given the evidence linking regret to the orbitofrontal cortex (Camille et al., 2004; Coricelli et al., 2005) and the findings of reduced spontaneous counterfactual thinking in orbitofrontal patients (Beldarrain et al., 2005). This latter study suggests that it may only be spontaneous counterfactual thinking that is linked to the frontal cortex. If this is the case, our lack of hemodynamic differences could be due to the nature of our counterfactual task. We primed individuals to have counterfactual thoughts by showing them "I should have" sentences in the counterfactual condition. This type of task is different from tasks looking at spontaneous counterfactual thoughts, which typically have an individual talk about or write down what they are thinking about something, such as a negative event in their own past.

We observed higher maximum percent changes of oxyHb overall in the left hemisphere than the right hemisphere. This is not surprising, given the numerous findings linking language processes to the left hemisphere, and the fact that our task was a task that utilized language.

We observed similar levels of most extreme percent change in the frontal cortex for processing realistic and unrealistic sentences. There was, however, a significant interaction of hemisphere and realism on maximum percent changes of oxyHb in the frontal cortex. In the left hemisphere there were higher maximum percent changes of oxyHb for unrealistic than realistic trials, while in the right hemisphere maximum percent changes of oxyHb were higher for realistic than unrealistic trials. Although none of the pairwise comparisons of realistic and unrealistic trials in the left and right hemisphere reached significance, this significant interaction provides evidence that the right hemisphere may have a more important role in the processing of realistic information than unrealistic information. The left hemisphere on the other hand, might have a more important role for processing unrealistic than realistic information.

There is another possible interpretation of this effect. In the unrealistic trials, there was a degree of cognitive conflict that was not present in the realistic trials, because for the unrealistic trials participants responded by answering that they didn't agree with the response sentence. It may be that the different levels of maximum percent changes of oxyHb in the two hemispheres for realistic and unrealistic trials were due to effects of this conflict. However, since the data was deconvolved from the onset of the response sentence rather than the response time, response conflict is not likely to fully explain the different levels of activation.

Limitations and Directions for Future research

Several limitations in this study can be addressed with future research. One drawback of the current study is the small sample size used. Differences in hemodynamic activity and performance between the counterfactual and causal tasks could have been occluded by low power. Another drawback is that the NIRS maps of concentration changes were not aligned with structural images, making it difficult to know the specific brain regions that we examined. This is further complicated by the fact that the relative locations of the structural markers (ears and eyebrows) we used to position the NIRS probe sets differed from participant to participant. Furthermore, differences in accuracy and response time may have been occluded by task difficulty. Since all participants had near perfect accuracy across conditions, there likely was a ceiling effect on accuracy.

Future studies should investigate neural activity that is associated with spontaneous counterfactual thinking, since it is this type of thinking that is impaired in frontal patients (Beldarrain et al., 2005). The challenge is to design a study that has both a task that naturally elicits counterfactual thoughts and a well-matched control task. Researchers should not constrain their studies to the dorsolateral prefrontal cortex. Since the present study showed no differences in levels of most extreme percent change of hemoglobin in the dorsolateral prefrontal cortex and surrounding regions, future studies should also look at other areas, such as the orbitofrontal cortex. Another important area of research will be to examine the cognitive and neural processes underlying realistic and unrealistic thinking. The neural correlates for counterfactual thinking may be different for different types of counterfactual thoughts.

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