J Psycholinguist Res (2015) 44:533–544
DOI 10.1007/s10936-014-9297-3

Deductive Versus Probabilistic Reasoning in Healthy Adults: An EEG Analysis of Neural Differences

Evie Malaia · Jodi Tommerdahl · Fred McKee

Abstract This study examined the electrophysiological signatures of deductive and probabilistic reasoning. Deduction is defined as the case in which a conclusion can be found to be true or false due to validity of argument. In probabilistic reasoning, however, conclusions can be considered to be likely or unlikely, but not with certainty due to the lack of validity in the form of the argument. 16 participants were presented with both types of arguments while response times and ERPs were carried out. Participants had to decide with the presentation of each argument, what type of reasoning was appropriate and which of four responses (certainly yes, probably yes, probably no and certainly no) was the most appropriate. Response times indicated faster processing of deductive arguments. N2 amplitude distinguished between positive and negative responses in the deductive condition, but not in the probabilistic one, suggesting partial differentiation between the cognitive processes required for the two types of reasoning.

Keywords EEG · Reasoning · Probabilistic · Modus ponens · Deduction

Introduction

Human's ability to reason, to evaluate the relationship between premises and potential conclusions, is a hallmark of higher cognition. Reasoning ability allows us to produce and extrapolate new knowledge based on given information, whether complete or incomplete. Various approaches to reasoning and linguistic reasoning have been studied intensively in philosophy and logic throughout centuries, and, much more recently, by neuroscience (Parsons and Osherson 2001; Goel and Dolan 2004; Prado et al. 2010; Tsujiia et al. 2011). The types of reasoning are historically divided into two major categories. When the given information (the premises) entails the truth value of the conclusions, the reasoning is con-

---

Evie Malaia and Jodi Tommerdahl have contributed equally to this work.

E. Malaia (✉) · J. Tommerdahl · F. McKee
Department of Curriculum and Instruction, Southwest Center for Mind, Brain and Education, University of Texas at Arlington, 701 Planetarium Place, Hammond Hall #417, Arlington, TX 76010, USA
e-mail: malaia@uta.edu

Table 1 Sample stimuli for deductive, probabilistic and comprehension conditions

Premises	Potential conclusions	Expected response
A. If the man falls down the stairs, he will break his leg.	Will he be injured?	Certainly yes
B. The man falls down the stairs.	Will he be unhappy?	Probably yes
A. If the boys eat ice cream at night, they will be full when they go to bed.	Are they hungry?	Certainly no
B. They ate ice cream at night and are going to bed.	Are they full?	Certainly yes
	Are they happy?	Probably yes
	Are they spoiled?	Probably yes
A. If Ken trains hard, he wins all his games.	Does he win?	Certainly yes
B. Ken trains hard.	Does he lose?	Certainly no
	Does he celebrate?	Probably yes
	Does he complain?	Probably no
	Does he train?	Certainly yes (probe)
A. If Mike the Monkey claps three times, he will get rewards including a banana.	Will he get fruit?	Certainly yes
B. He claps three times.	Will he get praise?	Probably yes
	Will he get food?	Certainly yes
	Will he get chocolate?	Probably no

Deductive arguments require a response of ‘certainly yes’ or ‘certainly no’ while probabilistic arguments require a response of ‘probably yes’ or ‘probably no’

sidered deductive; when the premises do not entail the conclusion but, rather, suggest them (given certain prior experience on the part of the reasoning individual), the reasoning is considered probabilistic. Table 1 provides examples of conclusions drawn from the same premises using two different types of reasoning.

Although both types of reasoning are pervasive in everyday communication, and expertise in both is assumed in competent adults, the psychological and neural resources used in reasoning are not well understood. The neural underpinnings of deduction have been studied somewhat more than those of probabilistic reasoning (see Goel 2007; Prado et al. 2011), with a small number of studies which have directly compared the neural activity of the two reasoning types which each ask the question of whether deductive and probabilistic reasoning are indeed separate processes that use different neural resources. The present study investigated this question by asking whether neurophysiological signatures of brain activity during deductive and probabilistic reasoning indicate divergent neural timelines for the two types of processing.

Two major theories that speak to this question of possible neural differentiation between the types of reasoning are Mental Logic theory and Mental Model theory. Mental Logic theory (Boole 1848; Braine 1978; Henle 1962; Rips 1994, 2001) proposes that humans have a set of mental inference rules or *schemas* which can be applied to natural language, allowing to create and evaluate formal arguments. An example of such an inference schema would be that of modus ponens: “If A, then B; A; therefore, B.” According to this theory, deductive reasoning is carried out through successful application of these rules to natural language. Other types of reasoning, such as probabilistic reasoning, cannot appropriately use these rules, and therefore must be based on an alternative system.

Mental Model theory (Johnson-Laird and Byrne 1991), on the other hand, takes a unitary approach, claiming that a single psychological mechanism carries out both deductive and probabilistic reasoning by constructing as many mental models of the premises as possible. A potential conclusion is inserted into each mental model and is evaluated for its truth value in each model. If the conclusion fits into each model without contradiction, the conclusion is considered to be true, whereas if it fits into most, but not all of the mental models, the conclusion is considered to be merely probable.

Both theories suggest that their processing models apply at the neural level—i.e. it should be possible to examine neural activity during the two types of reasoning to see whether they are identical or different. Although a large body of research exists on the neural mechanisms of deduction, neuroimaging studies which directly compare deductive and probabilistic reasoning are few (Goel et al. 1997; Osherson et al. 1998; Parsons and Osherson 2001; Goel and Dolan 2004). Each of these studies has found at least partial separation between neural areas used for the two types of reasoning; however, the localizations proposed across studies are inconsistent and sometimes contradictory. Possible reasons for the differences in findings include the use of different stimuli, tasks, experimental designs, and the measurement and sampling techniques used (Goel 2007).

Several EEG studies addressed the question of neural substract of deductive reasoning as well (Qiu et al. 2007, Bonnefond and Van der Henst 2009; Bonnefond and Van Der Henst 2013; Prado et al. 2008, inter alia). However, to the best of our knowledge, this is the first study using EEG in a *direct* comparison on deductive versus probabilistic reasoning. The study had two main goals: to determine whether deductive and probabilistic reasoning generate similar neural signatures, and to contribute to the discussion about the timecourse of deductive and probabilistic reasoning.

According to Mental Model theory, the nature of the difference between deductive and probabilistic reasoning is the rule-based nature of reasoning in the former. Then, if rule-based reasoning uses a different set of neural networks, we can hypothesize that electrophysiological "signatures" of the two types of reasoning should differ, especially in those cases where the correct reasoning yields *negative* answer. To assess whether conclusions supported by the two reasoning types are correct or incorrect, one has to carry out steps in the processing of a *deductive yes* and a *deductive no* that will differ from each other in ways that a *probabilistic yes* and a *probabilistic no* do not. As an example, let us consider the processing required to identify (potentially) correct conclusions among the four following these two premises:

A. If the baby is crying, her face will be wet.
B. The baby is crying.

1) *Is her face wet? (deductive yes)*
2) *Is her face dry? (deductive no)*
3) *Is her face red? (probably yes)*
4) *Is her face calm? (probably no)*

After accepting the premises in this example, a mental logic system is likely to correctly conclude that the baby's face is wet, even before any potential conclusions are provided on screen. However, the presentation of the second question asks the participant to consider that the baby's face is dry, which is in direct contradiction of the initial conclusion of being wet. During logical processing, the introduction of the notion of the face being dry is deemed to be logically impossible without breaking the rule of modus ponens. We predict that a *deductive no* answer may show signs of this clash between the valid conclusion and a contradictory conclusion that breaks the rule.

Let us consider the reasoning during assessment of probabilistic conditions. After processing the given premises, question 4, *Is her face calm?*, is similar to question 2 in that both may seem unlikely and surprising and result in a negative response. However, although number 4 may contradict the participant's own life experiences, it *does not break a logical rule.*

Thus, if a difference is shown to exist between the *yes* and *no* answers in deductive reasoning, it is of great interest to determine whether the same difference exists between the *yes* and *no* answers in probabilistic reasoning. If the same difference exists between each, this would indicate processing similarity between the two types of reasoning. However, if the difference *only* exists for *deductive reasoning*, this could suggest the use of different processing networks for the two reasoning types.

The EEG component that is sensitive to a clash between contradicting pieces of information is the N2, a frontally distributed negative deflection occurring around 200 and 300 ms post-stimulus, and related to the monitoring of conflict (Azizian et al. 2006). N2 typically co-occurs with a subsequent positive deflection, P3; both are sometimes referred to as N2–P3 complex. Thus, in this study, we hypothesized that increased amplitudes of the N2–P3 complex would differentiate deductive and probabilistic reasoning conditions with regard to *negative responses*.

In the same vein as the studies discussed above, the current study directly compares deductive and probabilistic reasoning through their underlying neural activity. However, this study attempts to go a step further by overcoming some of the difficulties present in earlier studies. Each of these attempts at improvement are described below.

The first major difference between the current study and others that have directly compared deductive and probabilistic reasoning is the nature of the stimuli presentation. Out of the several studies in the field (Goel et al. 1997; Osherson et al. 1998; Parsons and Osherson 2001; Goel and Dolan 2004) only Goel and Dolan varied the stimuli according to condition, and then only half of the arguments in the *deductive* condition were logically valid. In the current study, all of the stimuli in the *deductive* condition were of the form where the response was logically entailed and none of the arguments in the *probabilistic* condition had logical entailment.

This was possible due to a second factor which was our decision to randomly mix the stimuli as opposed to presenting them in blocks. Upon the presentation of each argument, the participant was required, with no instruction, to implicitly decide whether the stimulus was deductive or probabilistic and this was shown by their response. This was possible because possible responses were not binary. Instead, premises were provided and participants were asked to categorize potential conclusions with one of four conclusions 'certainly yes', 'probably yes', 'probably no' and 'certainly no'. This combination of tasks was different from those described above in that participants were not explicitly told to reason in a certain way and they were required to evaluate both whether an argument was valid or invalid and whether it was true or false (or likely or unlikely). These constant and rapid shifts between deductive and probabilistic reasoning are highly representative of how humans must reason in everyday life.

Because of the participants' choice between four responses, it was possible for the researchers to differentiate between an error made in the *deductive* condition that was judged by the participant to be probabilistic (by responding with a 'probably yes' or 'probably no') or that was given an incorrect deductive answer (for example, by responding with 'certainly no' when 'certainly yes' was the correct response.) Furthermore, this allowed us to closely examine responses in the *probabilistic* condition and to determine whether in the case of 'disagreement with expected answers' whether the participant had chosen a different probabilistic answer (choosing 'probably no' when 'probably yes' was expected) or whether a probabilistic question had been interpreted as deductive (answering with 'certainly yes' when 'probably yes' was expected). These distinctions allowed us to omit both incorrect responses from the *deductive* condition and unexpected responses from the *probabilistic* condition as well as to observe how often one condition was confused with the other.

Methods

Participants

Participants were 19 monolingual English speakers (9 female, aged 20–34, *M* = 25.1, *SD* = 4.24), right-handed according to handedness inventory (Oldfield 1971), with no history of neurological or speech-language impairments. All participants were administered the Wechsler Abbreviated Scale of Intelligence (Wechsler 1999, sections 1 and 3) to provide a baseline measurement of perceptual language and grammar processing ability (combined score *M* = 123.8, *SD* = 8.9).

Materials

The stimuli consisted of two premises followed by a question which presented a potential conclusion for evaluation. The relationship between the premises and the questions fit into one of three categories. In the deductive condition, the question can correctly be answered with certainty using the answers ‘certainly yes’ or ‘certainly no’. In the probabilistic condition, the question cannot be appropriately answered with certainty and the premises were designed to elicit an answer of either ‘probably yes’ or ‘probably no’. The final comprehension category asked a question which required no inference to be made, but asked for information already stated in the premises and was used as both as a filler and to ensure task comprehension. Stimuli from the three categories were presented in pseudo-random order in order that the participant had to distinguish between the conditions with each presentation of a new question. As there is an objective distinction between deductive and probabilistic arguments, no difficulty exists in the division of these categories. However, all stimuli in the probabilistic condition were assessed for suggestiveness of conclusions by two linguists, a neuropsychologist and a logician. Examples of the stimuli questions are presented in Table 1.

Eevoke version 3.1 (ANT Software, Netherlands) was used to present the stimuli. 28 sets of premises and a total of 135 questions were used. Each argument in the deduction condition used the modus ponens form. Each set of two premises appeared fully on the screen for three seconds each and were followed by two to four questions. Each question was presented in a word-by-word format as to avoid eye movement during testing. In each question, the last word remained on the screen for three seconds to allow sufficient time for participants to answer. The final word of each question was the only difference between the conditions and this word only determined what kind of response would be appropriate. The participants were seated in a sound-attenuating booth, and responded to each potential conclusion with one of four keys (*certainly yes, probably yes, probably no, certainly no*) to answer each question based on the premises.

Procedure

Participants signed an informed consent form, completed the handedness inventory, and were administered sections 1 and 3 of WASI. The ANT Waveguard electrode cap was fitted on each participant, and impedances lowered to less than 50 k Ohms. The participants were then seated in a sound-attenuating booth, about 60 cm from a 67.5 cm monitor. The experimental procedure was explained, and participants were given a practice session consisting of premises and potential conclusions in the form of a question for evaluation. Each participant took part in a practice session where the distinction between the answers with ‘certainly’ and ‘probably’ were discussed and practice arguments were provided. Each participant displayed an appropriate understanding of this distinction during the practice session. After the practice session, all subjects indicated that they were sufficiently familiar with the task to begin the experiment. Keypad response positions were counterbalanced between the right and left hands across subjects. The stimulus sentences were presented one-by-one on an LCD screen for 3,000 ms, with an interval of 500 ms between sentences. The premises were presented in their entirety while the sentences requiring a response were presented one word at a time, with 500 ms between words, to eliminate lateral eye movement during the answering phase. The run time for stimuli presentation and responses was approximately 25 min.

Event-Related Brain Potential Recordings

EEG activity was recorded from the scalp using 32 Ag–Cl electrodes secured in an elastic WaveGuard cap. Electrodes were positioned over homologous locations across the two hemispheres according to the criteria of the international 10-10 system (American Electroencephalographic Society, 1994). The specific locations of electrodes were as follows: midline sites FZ, FCZ, CZ, CPZ, PZ, OZ; medial–lateral sites FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6, C3/C4, P3/P4, P7/P8, T7/T8, O1/O2. Reference electrodes were placed over the left and right mastoids. Electroencephalographic activity was recorded referenced to the left mastoid; activity over the right mastoid was also recorded. All scalp electrodes were re-referenced to the average of the left and right mastoid off-line (Luck 2005). The eye movements and blinks were monitored and recorded using electrodes placed over the right and left outer canthi (horizontal eye movement), and left inferior and superior orbital ridge (vertical eye movement). The electrical signals were digitized online (ASA 4.7.1) at the rate of 512 Hz.

Data Analysis

For ERP measures, trials with excessive eye movements or other forms of artifact were rejected (under 20 % for each condition; the number of rejected trials did not vary significantly among the four conditions [(Fisher’s $p > .05$, *ns*)]. The recordings from 3 participants were discarded due to excessive motion artifact. On the EEG data from remaining 16 participants (9 female, age 20–34, $M = 25.1$, $SD = 4.24$), the recordings from individual participants were filtered at 0.1–7 Hz, baseline-corrected using 100 ms pre-stimulus interval, and individual averages were computed from 100 ms pre-stimulus onset to 800 ms post-stimulus for each of the single-word stimulus questions. Only the correct answers in the deductive condition and the expected answers in the probabilistic condition were analyzed. Statistical analyses included ERPs recorded at 26 scalp electrodes (medial sites FZ, FCZ, CZ, CPZ, PZ,OZ; fronto-temporal lateral and mid-lateral sites FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6; parieto-occipital lateral and mid-lateral sites C3/C4, P3/P4, P7/P8, T7/T8, O1/O2).

Measurements of peak amplitude were quantified in relation to the baseline voltage in each participant’s averages. Each ERP component was measured using a temporal window approximately centered around its peak in the grand averaged waveforms. The components of interest (N2, P3) were selected based on the differences between conditions in the data. The comparisons were made for N2 and P3 peak amplitudes and latency. Medial–lateral, and central electrode sites were analyzed separately.

Results

Behavioral Results

Participant responded with high degree of accuracy (94 %) to the control condition, indicating successful comprehension of the task. A two-way ANOVA with factors reasoning type (deductive, probabilistic), response valence (yes, no), was performed on accuracy and response latency measures. Among the reasoning conditions, participants responded with significantly higher percentage of accuracy (or higher degree of "expected answers") to stimuli requiring deductive reasoning [$F(1, 18) = 22.172$; $p < .001$, $e_p^2 = .581$, $M = 87.3\,\%$, $SD = 1.5\,\%$], versus probabilistic ($M = 64.3\,\%$, $SD = 3.1\,\%$). This was anticipated, since probabilistic reasoning does not produce "correct" answers, and depends on life experiences which vary between individuals. The valence of correct response (*Yes* vs. *No*) was also a significant main effect [$F(1, 18) = 6.704$; $p < .02$, $e_p^2 = .295$] as participants were much more likely to give an expected "Yes" answer.[1]

Response time latencies demonstrated effects of reasoning type [$F(1, 19) = 62.556$; $p < .001$, $e_p^2 = .796$], valence [$F(1, 18) = 41.776$; $p < .001$, $e_p^2 = .723$], and reasoning type × valence interaction [$F(1, 19) = 20.318$; $p < .001$, $e_p^2 = .559$]. Post-hoc paired-samples t-tests indicated significant differences between deductive positive and deductive negative conditions ($t = -8.639$, $p<0.01$), deductive negative and probabilistic negative ($t = -5.081$, $p<0.01$), and deductive positive and probabilistic positive ($t = -8.899$, $p<0.01$), but not probabilistic positive and negative ($p>0.05$). Participants responded faster to stimuli requiring deductive reasoning that probabilistic one (Fig. 1); response times in deductive reasoning condition were more affected by the valence of correct response (RTs latency for control condition −1.438 s, deductive *Yes*: $M = 1.253$ s, $SD = .2$ s; deductive *No*: $M = 1.515$ s, $SD = .22$ s; probabilistic *Yes* $M = 1.7$ ms, $SD = .19$ s; probabilistic *No* $M = 1.737$ s, $SD = .27$ s).

ERP Results

A four-way ANOVA with factors reasoning type (deductive, probabilistic), response valence (yes, no), laterality (anterior, posterior),[2] and hemisphere (left, right) was performed on peak minima and maxima in 180–220 and 220–350 ms windows (N2 and P3, respectively), and the mean amplitude in the 350–800 ms window post-onset of each final word in the question. We report results after Greenhouse-Geissner correction.

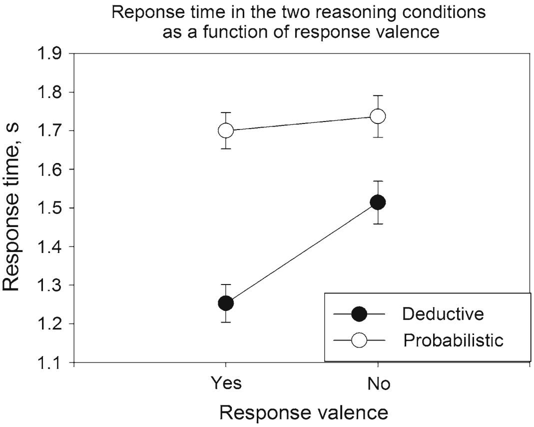
Response valence significantly affected amplitude of N2 and P3 components [$F(1, 15) = 8.678$; $p < .01$, $e_p^2 = .367$ and $F(1, 15) = 5.978$; $p < .027$, $e_p^2 = .285$, respectively]. A step-down ANOVA within each reasoning type indicated that valence effect over N2 was due to the differences in EEG response to affective valences in the deductive condition only [$F(1, 15) = 5.122$; $p < .038$, $e_p^2 = .242$]. Response valence significantly affected N2 amplitude over

---

[1] The errors in behavioral responses fell into two categories: when participants mixed the probabilistic and definite versions of "Yes" or "No" responses (e.g. answered "probably yes" when the correct answer was "certainly yes", etc.); and when they responded "no" to a condition requiring a "yes" answer (in either category). Participants gave a "Certainly yes" responses, when "probably yes" was expected, in 13.7 % of the probabilistic reasoning cases, and gave "probably yes" responses, when "certainly yes" was expected in 6.7 % of deductive reasoning cases. When negative response was the correct one, the participants used "certainly no" instead of "probably no" in 16 % of probabilistic reasoning cases, and "probably no" instead of "certainly no" in 11.5 % of deductive reasoning cases.

[2] Anterior electrodes included fronto-temporal lateral and mid-lateral sites FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6; posterior electrodes included parieto-occipital lateral and mid-lateral sites C3/C4, P3/P4, P7/P8, T7/T8, O1/O2.

Fig. 1 Response times in the deductive, but not probabilistic condition were affected by response valence. Error bars indicate standard error



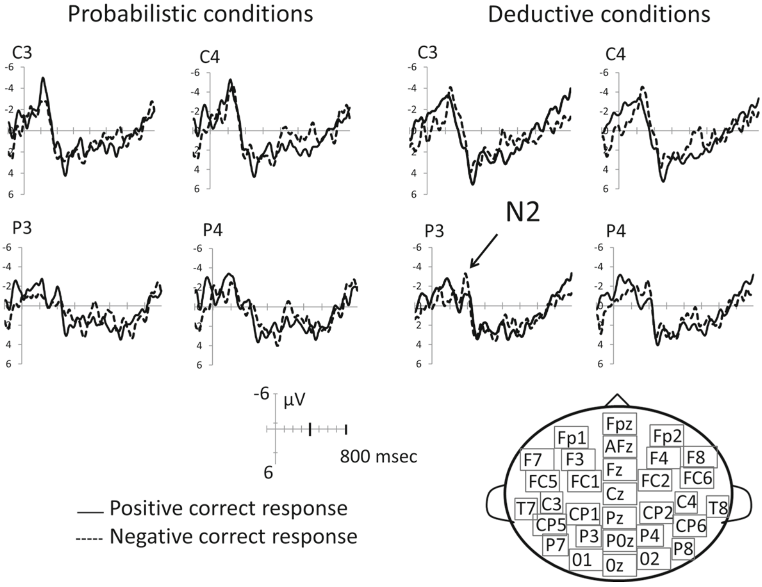


Fig. 2 Morphology of the N2 component in probabilistic and deductive conditions, showing both negative and positive responses (*dotted* and *solid lines*, respectively) over the representative electrodes for each laterality-hemisphere quadrant: C3, C4, P3 (indicating statistically significant differences over left posterior N2), and P4

the fronto-temporal, parieto-occipital lateral and mid-lateral sites, such that during deductive reasoning, negative valence of the response elicited a larger deflection of the N2 waveform (Fig. 2).

Step-down ANOVAs within each reasoning type (with factors response valence (yes, no), laterality (anterior, posterior), and hemisphere (left, right) did not reveal any other statistically significant effects on N2 latency, P3 latency or amplitude,[3] or mean amplitude in the

---

[3] The effect of response valence on P3 amplitude in omnibus ANOVA did not appear significant in post-hoc step-down analyses.

350–800 ms window over the fronto-temporal and parieto-occipital lateral and mid-lateral sites, or central sites [$F(1, 15) < 1$].

Discussion

For both types of reasoning, positive answers were given more quickly than negative ones, although the difference was not statistically significant in the probabilistic condition. However, both positive and negative responses in the deductive condition were faster than either a positive or negative response in the probabilistic condition. This indicates that probabilistic reasoning might carry a higher processing demand than deduction, as probabilistic reasoning involves the activation of long term memory to search for past events that might support or weaken the proposed conclusion. This matches well with the description of mental model theory, but only in terms of probabilistic reasoning. The relative swiftness of deduction could be analyzed as support for mental logic theory which proposes that humans have a rule-based mental inference schema, which can be used to solve logically valid problems with relative speed.

An important advantage of this study was the use of differing stimuli for each condition. In past studies, even when differing stimuli were used, half of the arguments used in the deductive condition were invalid, thereby possibly inviting probabilistic analyses. This study replaces the valid and invalid arguments used to stimulate deductive reasoning with valence-based answers, with each requiring the use of modus ponens. This led each participant to make two decisions, with one regarding whether deductive or probabilistic reasoning should be used and the other asking whether the response should be negative or positive. As the arguments were mixed, as opposed to being presented in blocks, the participant relied solely on the argument form in order to choose a response. This design brings about various advantages. Because four possible responses were possible, it was possible to determine when deductive arguments were treated as if they were probabilistic and vice versa. Also, this presentation of reasoning which is not based on instructions, but is instead based on a direct reaction to the arguments themselves, is more representative of real-life reasoning. Finally, it allowed us to take the conservative action of not only rejecting incorrect answers in the deductive condition but also made this the first study to reject unexpected answers in the probabilistic condition, leaving us with data that is the most likely to truly represent each of the two reasoning systems.

The N2 observed in response to the negatively-valenced deductive condition draws attention to a somewhat incomplete description of the N2 in the current nomenclature of EEG components. In general, negative deflections around 250 ms post-stimulus have been observed in two types of ERP experimental designs: emotional processing, and the visual oddball paradigm. In order to understand the cognitive processes underlying emergence of the N2 component in the present paradigm, we need to identify what reasoning has in common with the two, as the presence of a specific component in the waveform does not equate to the presence of a specific cognitive processing step; a component might indicate a convergence of several active sources contributing to the overall waveform morphology.

Studies of emotion identify central, or centro-parietal deflection around 250 ms post-stimulus (termed N2 or, alternatively, EPN—early posterior negativity) as an index of selective attention to visual features of the stimulus (see Hajcak et al. 2012, for review).Visual paradigms distinguish several negative components—anterior N2, and posterior N2pb/N2pc, which differ in distribution and concomitant morphology of the ERPs (see Luck 2011, for review). Anterior N2 is typically observed as a part of P2–N2 complex in response to incompatible task-related visual features in popout, flanker, and Stroop tasks. Posterior negative deflection is observed bilaterally (N2b), or contralaterally (N2c) to the side of presentation of the target visual item in popout tasks, typically followed by the larger, opposite polarity P3 waveform. It has been suggested that the posterior N2 might reflect the process of categorizing a stimulus (Renault et al. 1982), since its duration is increased in more demanding conditions. However, in the present study, visual observation of individual and group waveforms indicated that overall morphology of ERP to disambiguating words in the questions did not include P2 or P3 components. Prior EEG studies of deductive reasoning have also found the N2 component in deductive condition: Prado et al. (2008) identified a frontocentral N2 in response to negation in stimuli sentences, while Bonnefond and Van der Henst (2009); Bonnefond and Van Der Henst (2013) found a similar component in response to linguistic mismatches between premise and conclusion (similar to those we used in both deductive and probabilistic conditions). In the present study, however, the N2 component in negatively valenced deductive condition likely indexed selective attention during cognitive processing, related to the negative outcome of deductive reasoning process. As we did not observe the N2 component in the probabilistic condition in the present study, we can extend the understanding of the N2 as the earliest neural marker of lack-of-positive conclusion in (language-based) deductive reasoning.

Not all studies of deductive versus probabilistic reasoning agree with the assessment of relative difficulty of the two tasks. While Parsons and Osherson (2001) report that induction was rated slower and more effortful by eight out of ten participants, Goel and Dolan (2004) recorded reaction times showing deduction to be the slower activity. This difference is likely to be due to differences between the nature of the stimuli. While Goel and Dolan used categorical syllogisms, this study, like Parsons and Osherson's, used conditional statements. These differences are not surprising and highlight the fact that none of these studies are able to fully examine the entireties of deductive and probabilistic systems, but are instead limited to specific reasoning types in specific design-defined contexts. The difference that we found between the systems does not mean that the mental models/mental logic narrative is the appropriate one. Evans (2006) makes the distinction between 'dual processes', which claim that the processes discussed are sharply different both in their evolutionary histories as well as their neurological substrates, and 'dual-system theories' which are broad, not easily applied to specific cognitive tasks and that are often couched in controversial theory. It is indeed difficult to identify the point at which neurological differences become sharply divisive but it is doubtful that the findings here could be categorized as such. It is also difficult to categorize the findings within Evans' description of dual-system theories seeing that the results are from experimental and very specific cognitive tasks. While our findings are not strongly supporting a particular theory, they do indeed indicate a distinction between deductive and probabilistic processing that could be due to the rule-based nature of the former.

Conclusions

This experiment is among the first studies to mix deductive, probabilistic and comprehension conditions in their presentation to participants as opposed to other studies that divide conditions into separate blocks. This combination of conditions simulates a more naturalistic task reflecting the way that humans take in information.

Until now, little was known about the timecourse of neural resource allocation during deductive and probabilistic reasoning. Our work demonstrates rapid (within 200 ms) allocation of attentional resources to the evaluation of deductive conclusions. The probabilistic conclusions, on the other hand, are evaluated more slowly, and possibly engage episodic working memory resources. These findings support the notion of a degree of separation between the neural processing of deductive and probabilistic syllogisms.

The possibility put forward by this study that ERPs can be used to identify and monitor a logical rule or inference schema is an exciting one. An ability to target an inference schema using neurological tools will be useful in learning about the application and evaluation of these rules in different populations. Of particular interest will be what Braine (1978) called a "critical question" of what the developmental origins are of logic. Brain studies, along with existing behavioral ones, will be of use in the future in determining when and how these inference schemas come about.

Further research into the neural mechanisms underlying reasoning is of use not only to researchers constructing cognitive architectures, but also to health-related practitioners. A deeper understanding of our reasoning systems may serve patients with traumatic brain injury or neurogenerative disorders that exhibit impaired reasoning as one of its primary symptoms (schizophrenia, dementia, etc.). Future research will also serve our understanding of normal aging in the brain as well as human mechanisms of learning throughout the lifespan.

References

Azizian, Allen, Freitas, Antonio, Parvaz, Mohammad, & Squires, Nancy. (2006). Beware misleading cues: Perceptual similarity modulates the N2/P3 complex. *Psychophysiology*, *43*, 253–260.

Bonnefond, M., & Van Der Henst, J. B. (2009). What's behind an inference? An EEG study with conditional arguments. *Neuropsychologia*, *47*(14), 3125–3133.

Bonnefond, M., & Van Der Henst, J. B. (2013). Deduction electrified: ERPs elicited by the processing of words in conditional arguments. *Brain and Language*, *124*(3), 244–256.

Boole, G. (1848). The calculus of logic. *Cambridge and Dublin Mathematical Journal*, *3*(1848), 183–198.

Braine, M. D. (1978). On the relation between the natural logic of reasoning and standard logic. *Psychological Review*, *85*(1), 1.

Evans, J. (2006). The heuristic-analytic theory of reasoning: Extension and evaluation. *Psychonomic Bulletin & Review*, *13*(3), 378–395.

Goel, V., Gold, B., Kapur, S., & Houle, S. (1997). The seats of reason? An imaging study of deductive and inductive reasoning. *NeuroReport*, *8*(5), 1305–1310.

Goel, V. (2007). Anatomy of deductive reasoning. *Trends in Cognitive Sciences*, *11*(10), 435–441.

Goel, V., & Dolan, R. J. (2004). Differential involvement of left prefrontal cortexin inductive and deductive reasoning. *Cognition*, *93*(3), B109–B121.

Hajcak, G., Weinberg, A., MacNamara, A., & Foti, D. (2012). ERPs and the study of emotion. Oxford Handbook of ERP Components, 441–474.

Henle, M. (1962). On the relation between logic and thinking. *Psychological Review*, *69*(4), 366.

Johnson-Laird, P. N., & Byrne, R. M. (1991). *Deduction*. Hillsdale, NJ: Erlbaum.

Luck, S. (2005). An introduction to the event-related potential technique. Cambridge: The MIT Press.

Luck, S. J. (2011). Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components. *Oxford Handbook of ERP Components*.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Osherson, D., Perani, D., Cappa, S., Schnur, T., Grassi, F., & Fazio, F. (1998). Distinct brain loci in deductive versus probabilistic reasoning. *Neuropsychologia*, *36*(4), 369–376.

Parsons, L. M., & Osherson, D. (2001). New evidence for distinct right and left brain systems for deductive versus probabilistic reasoning. *Cerebral Cortex*, *11*(10), 954–965.

Prado, J., Kaliuzhna, M., Cheylus, A., & Noveck, I. A. (2008). Overcoming perceptual features in logical reasoning: An event-related potentials study. *Neuropsychologia*, *46*(11), 2629–2637.

Prado, J., Van Der Henst, J. B., & Noveck, I. A. (2010). Recomposing a fragmented literature: How conditional and relational arguments engage different neural systems for deductive reasoning. *Neuroimage*, *51*(3), 1213–1221.

Prado, J., Chadha, A., & Booth, J. R. (2011). The brain network for deductive reasoning: A quantitative meta-analysis of 28 neuroimaging studies. *Journal of Cognitive Neuroscience*, *23*(11), 3483–3497.

Qiu, J., Li, H., Huang, X., Zhang, F., Chen, A., Luo, Y., ... & Yuan, H. (2007). The neural basis of conditional reasoning: An event-related potential study. *Neuropsychologia*, *45*(7), 1533–1539.

Renault, B., Ragot, R., Lesevre, N., & Remond, A. (1982). Onset and offset of brain events as indices of mental chronometry. *Science*, *215*(4538), 1413–1415.

Rips, L. J. (2001). Two kinds of reasoning. *Psychological Science*, *12*(2), 129–134.

Rips, L. J. (1994). *The psychology of proof: Deductive reasoning in human thinking*. Cambridge, MA: MIT Press.

Stanovich, K. E., & West, R. F. (2000). Individual differences in reasoning: Implications for the rationality debate? *Behavioral and Brain Sciences*, *23*(5), 645–665.

Tsujiia, T., Sakatania, K., Masudab, S., Akiyamac, T., & Watanabeb, S. (2011). Evaluating the roles of the inferior frontal gyrus and superior parietal lobule in deductive reasoning: An rTMS study. *Neuroimage*, *58*(2), 640–646.

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. Psychological Corporation.