Windows for understanding the mind: Introduction to A Handbook of Process Tracing Methods for Decision Research

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“We need to open the black box of decision making …” (Rubinstein, 2003)

Al, the alien, is visiting earth for the first time. She came to earth in order to find out how humans make decisions. Since Al has no idea whatsoever about human choice, she starts by observing human choice behavior. This leads her to the insight that human choice actually follows some rules. For instance, humans nearly always choose houses over apples, and kisses over electric shocks. Thus humans seem to have strong preferences for houses, and kisses, respectively. However, Al is unable to find systematic preferences in other areas, such as the choice between swimming and sunbathing. Eventually, however, Al detects regularities between preferences. For instance, more of an item is usually preferred to less of it, e.g., humans prefer two apples over one apple. Al formulates her theory in the form of a structural model for predicting preference p by the attributes of items: $p=\alpha*n + \beta*w + \gamma*s + \ldots +\omega*z$ (with Greek letters indicating weights, and Roman letters indicating attributes).

Did Al manage to understand how humans make decisions? Note that Al, our alien friend, could have proceeded differently:

Al, the alien, is visiting earth for the first time. She came to earth in order to find out how humans make decisions. Since Al has no idea whatsoever about human choice, she begins by collecting reports of the processes that lead to those choices. Al listens to people thinking aloud while making choices and she learns about thoughts that precede and accompany choices. She then formulates a theory of human decisions based on careful analysis of these thoughts.

Al's choice of method points to a very old question in human philosophy and psychology: How can we best investigate thought processes? Introspection was once considered to be the royal road to understanding mental processes (Külpe, 1893), but it also had its opponents from the very beginning of scientific psychology (e.g., Wundt, 1907). One major development in the last century was a shift to methods allowing the direct observation of behavior. More recently, the 1990s have been named the "Decade of the Brain" (initiative by the Library of Congress and the National Institute of Mental Health), indicating a further shift from observation of behavior to observation of the brain. Thus, as time went by, various techniques were devised in order to advance from simple observation to deeper understanding of our cognitive processes.

Choices are the end result of evaluative processes. How can we know the ways and means that brought them about? We argue that unobservable cognitive entities – cognitive representations – are the key to this. This volume is about the methods devised in the field of judgment and decision making (JDM) to enable traces of cognitive processes to be identified.

WHAT IS PROCESS TRACING?

Cognitive science concerns the interdisciplinary study of the acquisition and the use of cognitive representations or, more generally, knowledge. In order to investigate the ways and means of knowledge use, a variety of methodologies have evolved in cognitive science: observational; simulation; physiological; neuroscientific and experimental. Among these methodologies several are subsumed under the label of “process tracing techniques”.

What exactly distinguishes a process tracing technique from other techniques? Let us take an example: Does the statement “I choose option A” which is delivered by a participant at the end of a choice experiment count as a process datum? In a sense, it describes a process, namely the process of stating a preference for option A. However, this statement fails as a true process measure, since it says nothing about the different steps necessary leading to the preference. A model of this process is needed to determine what counts as appropriate process data. For instance, if we take the subjectively expected utility (SEU) model as a possible model for risky choice, a process tracing study would look for evidence of multiplication of outcomes and probabilities; the statement of the outcome itself could never be used to trace the process. In contrast, if our model was a decision heuristic, we would look for quite different processes, such as the information search patterns necessary to execute it. Note that, according to this view, process tracing does not need repeated measurement. For instance, a single reaction time measurement may indicate some focal process in a valid way (see Chapter 6). Neither is it necessary to collect process data during the course of the process (although this frequently is the case, see Chapter 4), nor are process tracing techniques restricted to directly tracking hypothesized cognitive (i.e., internal, mental) processes. The latter requirement would be too restrictive, since physiological and neuropsychological data would then fail as process tracing methods. Rather, verbal (e.g., thinking-aloud, see Chapter 4), behavioral (e.g., eye movements, see Chapter 2), physiological (e.g., skin conductance, see Chapter 7), or neuropsychological (e.g., brain-scanning, see Chapter: Conclusions) data can be used to trace cognitive processes, as long as they are aiming at the hypothesized process. For example, the researcher hypothesizing that people rely on SEU in choosing among risky gambles would collect verbal phrases indicating that outcome and probability are combined in working memory - this would clearly qualify as a process tracing method. On the other hand, collecting reaction times would not qualify as a process tracing method here, since SEU, as a process model, is mute about reaction times. However, if the researcher hypothesized that thinking is superficial and fuzzy, collecting reaction times would in a valid way indicate the process of fuzzyfication, since the model predicts identical reaction times for easy and for complicated choices.

Taken together, most methods discussed here may or may not produce genuine process tracing measures. For data to be appropriately classified as process measures (i) a process model of dynamic changes in cognitive or affective parameters is necessary, and (ii) the collected data must clearly relate to the hypothesized dynamic processes.

OVERVIEW OF PROMINENT PROCESS TRACING METHODS

For the purpose of this handbook we suggest a loose classification of process tracing methods that distinguishes among (i) methods for tracing information acquisition (e.g., information boards); (ii) methods for tracing information integration and evaluation (e.g., thinking aloud); and (iii) methods for tracing physiological, neurological, and other concomitants of cognitive processes (e.g., skin conductance). This classification is based on the main purpose of the various methods. We are perfectly aware, however, that any method can, in principle, be used for multiple goals (e.g., thinking aloud can yield information about information acquisitions, as well as about information integration). In what follows we will describe the central measures collected by each of the methods presented in this volume.

Methods for Tracing Information Acquisition

We will introduce three methods for tracing information acquisition patterns in this section: Information boards, eye tracking and active information search. Information acquisition is often monitored using one of these methods, but bear in mind that only perceived information can be traced by these techniques. Retrieval processes from memory, which are also important inputs for judgment and decision making processes, are beyond the reach of these techniques and have to be inferred. Consequently, the interpretation of search patterns is more problematic the more memory processes are involved.

Information boards

With this method, participants acquire information, for instance, by opening envelopes that contain cards with text on them. Payne (1976) pioneered the development of this technique which provides data concerning the content, amount, and sequence of information explicitly acquired on such literal information boards. In recent years the information board approach has become more sophisticated by using a variety of computer-controlled information retrieval systems (see chapter 1). Well known among these is the Mouselab system (Bettman, Johnson, & Payne, 1990; Payne, Bettman, & Johnson, 1993), which allows, in addition to the above mentioned variables, the measurement of the time (on a millisecond scale) associated with the acquisition of a particular piece of information. Critics argue that information board studies are limited in two ways: they almost exclusively rely on written information and they require some sort of information pre-structuring.

Eye movements

The recording of patterns of eye movement is a typical method of monitoring information acquisition. The idea is that eye movements are a window on cognitive processes (the “eye-mind hypothesis“; Just & Carpenter, 1980) since a good deal of visual information is accessed and processed during fixation. There are some serious problems with interpreting eye movements in reading and most notably in natural settings (see Hayhoe & Ballard, 2005). However, these are less critical in JDM research which often involves interpreting patterns of eye movement with less complex stimuli. Parameters of particular interest are saccadic movements and fixations. To infer cognitive processes the tempo, amplitude, duration, or latency of saccadic movements, and the duration, frequency, and scanning path of fixations have been used (see chapter 2). Eye-movement data have been collected for over 100 years now and it is our impression that this technique has been increasingly used in recent years.

Active information search

Earlier we mentioned the pre-structuring of information as a possible downside of information boards; the method of active information search (AIS, see Chapter 3) focuses on this problem. In this method the participants get only a basic description of the task, and have to ask questions in order to receive additional information. This technique enables the unobtrusive observation of the participant's information needs and the testing of the influence of pre-structuring on thinking and decision making. In the standard method the type, frequency and sequence of the collected information is recorded. Computerized versions of AIS can also record the reading time for information items.

Methods for Tracing Information Integration

After having collected information by perception, the integration of this information is the next step towards a choice. Verbal self-reports have long been the royal road to investigate information integration. "Verbal self-report" is a term denoting the set of procedures that require people to report on their thought processes before, during, or after solving a task, or taking a decision.

Self-reports are easily and naturally delivered and are, though being subjective, direct descriptions of one's mental life. However, there has been much debate about their validity, reliability, and completeness (e.g., Ericsson & Simon, 1993; Nisbett & Wilson, 1977). Chapters 4 and 5 deal with focal aspects of collecting process data on information integration using thinking aloud and structured response elicitation.

Thinking aloud

The lion's share of self reporting is done verbally. Two classes can be differentiated: well structured self reports (e.g., a test), and loosely structured self reports (e.g., thinking aloud). Among the loosely structured techniques, concurrent verbal reporting is the main technique, sometimes accompanied by the recording of eye movements, bodily expressions or physiological reactions. Nisbett and Wilson (1977) formulated strong reservations against collecting verbal data, arguing that people report their subjective theories about what should be going on in their head during solving some problems, rather than reporting what is actually going on. Partly in response to this, Ericsson and Simon (1980; 1993) championed the use of concurrent verbal reports provided that the contents of working memory are in a verbal code. They argued that the more processing is necessary to transform working memory content into a verbal code the more questionable the method becomes (see chapter 4). Indeed, there is a lively discussion on the use of verbal data, indicated by two special issues of the Journal of Consciousness Studies devoted to the use of introspective evidence in Cognitive Science in the years 2003 and 2004 (Vol. 10, No. 9-10, and Vol. 11 No. 7-8).

Structured response elicitation

It seems that a remarkable amount of research (not only) in JDM consists of marks on self-report questionnaires. Participants are asked to report what they have done, will do, or would do. Frequently, participants have to report how they feel at a given time or why they do what they do. However, given the discrepancies between self-reports of past behavior, or hypothetical future behavior, and actual behavior, the value of such data is open to criticism. One obvious problem is the influence of different response scales. Preference reversals are a clear example of this problem, by showing that inconsistencies exist between choice and pricing (Lichtenstein & Slovic, 1971), choice and matching (Tversky, Sattath, & Slovic, 1988), and between separate and joint evaluations (Hsee, 1996). Note that these data show that response scales not only influence the expression of a preference, but also contribute to the formation of the preference itself. Thus, by using different response scales people actually may form different preferences, rather than identical ones that are expressed differently. Constructing rating scales on the fly, frequently based on face validity, may thus have serious shortcomings. A thorough discussion of these and other aspects is given in chapter 5.

Methods for Tracing Physiological, Neurological, and other Concomitants of Cognitive Processes

The third building block of this handbook investigates the recording of various concomitants of cognitive processes. We include reaction time as a special category, conceptually distinct from the others. The other methods trace changes in physiological or neural parameters that accompany cognitive changes. On the assumption that there are stable relationships between these parameters and mental experience that can be interpreted in a meaningful way (but see Kagan, 2007, for a critical position) these parameters can be tracked and interpreted as indices of cognitive processes (see chapters 7 to 9). Frequently, however, the meaning of these basic data for cognitive processes is open to debate. Most importantly, interpretation tends to be statistically tricky and ambiguous unless there is a very high degree of experimental control and comparability across participants. One of the most significant advantages of these techniques, however, is that they bypass the verbal system, thereby alleviating the problem of the ubiquity of verbal data as evidence for mental processes. Another advantage is that many biopsychological signals are not confined in the realms of consciousness and cannot be influenced at will. Among the parameters that have been collected for a long time in JDM research is the recording of electrodermal activity (e.g., the galvanic skin response), and of pupil dilation. More recent techniques focus on the neuronal level (e.g., functional magnetic resonance imagining).

Measurement of Reaction Time

The collection of reaction times does often not qualify as a process tracing method. However, if based on a process model and if corresponding to the hypothesized dynamic processes, reaction times can be used in this way. For instance, reaction-time measurement has been frequently used to indicate basic thought processes, and has left identifiable traces in the psychological literature (e.g., Donders' (1969/1868) elementary mental processes; Sternberg's (1966) memory scanning task; Cooper and Shepard's (1973) mental rotation task). However, reaction times contain little detailed information as to the processes consuming this time. There are actually many assumptions about basic mental processes that are necessary in order to interpret reaction times in a meaningful way. Moreover, only very simple tasks can be used, that can be segmented into still simpler steps. Therefore, isolated reaction time measurement often fails to be satisfactory as a process tracing technique. Chapter 6 discusses these and other issues of using reaction time data in JDM research.

Galvanic Skin Conductance

The galvanic skin response (GSR) measures the resistance of the skin to the passage of a very small electric current. The relationship between the magnitude of this electrical resistance and emotion has been known for decades. It seems that what is reflected in skin resistance is some overall degree of arousal: higher arousal does almost instantaneously cause a fall in skin resistance; reduced arousal causes a rise in skin resistance. More detail is given in Chapter 7.

As a tool for process tracing, GSR is mainly used with respect to emotions. A general problem, however, is that it fails to enable the identification of the specific emotion being elicited, or the source of the arousal. Fear, anger, startle or orienting responses, as well as sexual feelings are among the emotions which may produce similar responses. This is because, in physiology, emotions are predominantly described as points in a two dimensional space of affective valence and arousal (Lang, 1995). While the relationship between arousal and GSR is largely understood, the relationship between valence and this technique remains an open question.

Pupil dilation

The measurement of pupil dilation offers a remarkable portal to the inner workings of the brain. Pupil dilation measures the circular opening at the centre of the eye that contracts and dilates to regulate the amount of light the eye receives. As the proverb says, the eyes may be the windows to the soul. However, pupils dilate and contract not just in response to light levels, but also depending on the chemical state of the brain. For example, opiates cause the pupil to constrict to pinhole size, while ecstasy causes it to dilate. In the normal body, the pupils dilate largely in response to norepinephrine, the neurotransmitter responsible for our "flight or fight" response to dangerous situations. Detail in the use of eye-tracking and pupil dilation is given in chapter 8.

Neuronal techniques of location: Passive and active

Recently new and technologically advanced techniques have been used to investigate how cognitive functions are produced by the neural circuitry. As a whole, they are often termed neuroscience methods. The specific field that traces cognitive processes is called cognitive neuroscience, and overlaps with several sub-disciplines such as cognitive psychology, psychobiology, neurobiology, neurophysiology, neurology, and psychiatry. With respect to process-tracing, the promise of these techniques is to overcome a long-standing problem, namely that mental processes in JDM (e.g., the presumed preferences, or beliefs) are impossible or difficult to observe directly. Instead, their effects were thought to be revealed through choices or other behavioral measures. In research on reasoning, for instance, neuroscience methods have recently been used to decide among two major theories on deductive reasoning: whether deduction is underwritten by a system of (linguistic) rules sensitive to the logical form of the argument (mental logic theory; Rips, 1994), or whether a visuospatial representation of the argument is constructed and evaluated (mental model theory; Johnson-Laird, 1994).

We distinguish between passive and active techniques. Most important among the passive techniques is the measurement of electrophysiology by electroencephalography (EEG, and the use of imaging techniques like functional magnetic resonance (fMRI). An active technique is transcranial magnetic stimulation (TMS). Chapter 9 is dedicated to these techniques, most notably TMS. TMS is a method to excite or inhibit neurons in the brain by inducing weak electric currents in the tissue via rapidly changing magnetic fields. TMS is an experimental technique which can overcome the limitations of the passive techniques, which rely on correlation evidence. An overview over the findings with fMRI is given in the chapter Conclusions; but we will not discuss the recording of neurochemical parameters (see Peterson, 2007, for an example of the application of such research on economic behavior), nor methods measuring parameters of the endocrine and immune systems.

In this volume we argue that techniques of localization are process tracing studies, if they are testing process models (see our definition of process data above). For instance, a study by Tom et al. (2007) tested the prospect theory proposition that the outcomes of risky decisions are coded as gains or losses, relative to a reference outcome. They found brain areas showing increasing activity as gains increased (including midbrain dopaminergic regions), and decreasing activity in some of the same areas as losses increased. These findings can be interpreted in terms of processes proposed by prospect theory. Another example is the distinction between risk and ambiguity. Hsu et al. (2005) found in an fMRI study that the level of ambiguity in choices correlated positively with activation in the amygdala and orbitofrontal cortex, and negatively with activity in the striatal system. Thus, there is evidence of a neural basis for the distinction between risk and ambiguity, which is based on behavioral findings (ambiguity aversion) but fails to be reflected in classic theorizing (in subjective expected utility the probabilities influence choices whereas ambiguity does not).

PROCESS TRACING METHODS AND THEIR USE IN JDM RESEARCH

Now that we have outlined the most important process tracing methods we will try to answer a second question: What is the scientific inpact of these methods in JDM research and theorizing? To get an overall picture of the use of process tracing methods in recent JDM work, we ran an extensive literature search. Specifically, we searched PsycINFO for all English language papers published in reviewed scholarly journals using keywords related to process tracing methods. Following our division into three areas we searched for (i) methods for tracing information acquisition; (ii) methods for tracing information integration and (iii) methods for tracing physiological, neurological, and other concomitants of cognitive processes. We wanted to know how often methods from these three groups were used in JDM research.

Keywords

As keywords we used information *board**; *information search*; *mouselab*; and *eye movemen*t* for the methods for tracing information acquisition (group i). For the methods for tracing information integration (group ii) we used *introspection*; *phased narrowing*; *process trac*; protocol analys*; think* aloud*; *thought listing*; *verbal data*; *verbal protocol*;* and *verbal report*.* Methods for tracing physiological, neurological, and other concomitants of cognitive processes (group iii) were indicated by the keywords *blood pressure*; *EEG*; *electromyogra**; *fMRI*; *galvanic skin response*; *heart rate*; *neural correlat*; pupil dilation; and TMS.* We also searched for reaction time and latency as keywords; note that we treat reaction time as a separate fourth group, because it is conceptually distinct from the other methods. We limited our search to the judgment and decision making literature (keywords decision; choice; judg*ment). As a group for comparison, we also counted the papers in JDM excluding additional process tracing measures. We searched for the keywords in title and abstracts only.

Results and Discussion

Figure 1 depicts the findings of the overall search in terms of the number of hits for our four groups. Hits are averaged over time intervals of 3 years, beginning from 1970 until the end of 2008 (access date: 23-07-2009). The search resulted in 6783 hits overall. Since this is pure keyword search, without deeper examination of the results, this number is the upper limit, and some of the papers might not be adequately subsumed as belonging to JDM.

In order to check this, we randomly drew papers from the overall sample and investigated whether or not the respective paper was actually a “hit”. We did not come across many false alarms. Our best estimation is that, in general, not more than 5% of the papers are have been falsely counted as relating to process tracing methods in JDM research. Note, however, that incorrect counts may be more frequent in some specific combinations. For instance, the keywords ‘reaction time’ and ‘decision making’ may produce a number of hits that may not be central to the JDM literature (e.g., lexical decision tasks).

As can be seen in Figure 1 there was a steady increase in the number of papers dealing with process tracing over the last 40 years. This indicates a general trend of an increasing number of publications in the area of JDM, something that is probably true for nearly all areas of Psychology, however.

Insert Figure 1 about here

Of the 6783 hits for the period from 1970 until 2008 about 10% were related to information acquisition, another 10% to information integration, about 20% to physiological and neuronal activity, and the lion’s share of about 60% to reaction time. Figure 1 also shows that the number of hits for all methods increased considerably over the years, but especially methods measuring physiological and neural activity rocketed in the last 10 years.

That the increase was similar for all groups is also evident when we measured the relationships among groups by calculating the correlations between them. All correlations were extraordinarily high (between 0.81 and 0.94), indicating some common trend.

The above analysis in terms of number of hits shows the grand picture. Note however, that the trends of the four groups showed significant nonlinearity over the time interval, with all groups being best fitted by a power-function of the form $y=a* x^b$ (with all R^2 higher than 0.80, most of them even over 0.90), rather than a linear increase.

Figure 2 depicts the *relative* contributions of the different groups to the process tracing literature in JDM over the last 40 years. Calculated is the ratio of number of hits per time period divided by overall hits for each group. The message of this analysis is clear. There is a “loser”: the reaction time methods. Their relative share did decrease. Not surprisingly, the “winners” are the methods of measuring physiological and neural activity. The share of the process tracing techniques of groups 1 and 2 increased slightly.

Insert Figure 2 about here

As a measure of comparison we also counted the frequency of papers that used one of the keywords of decision, choice, or judgment in their abstracts and title section, but none of the other keywords for our process tracing measures. Overall, the search yielded 86602 hits in the period between 1970 and 2008. The increase was also considerable over the years: from a baseline of 2335 paper in the first period (1970 – 1972) the number steadily increased to 18893 hits in the last period (2006 – 2008). This is about 6 times as much. The corresponding numbers in the process tracing groups are 250 (1970 – 1972) and 1231 (2006 – 2008) – about 5 times as much. The trend was also nonlinearly increasing, and the correlation between process tracing studies and non-process tracing studies in JDM was high (r=0.98).

In sum, our literature search on process tracing studies published in refereed journals in the last 40 years shows that there was a steady increase in process tracing papers. From 1970 to 2008 the number of relevant papers rose by a factor of about 5 in the JDM literature. This increase is similar to the increase witnessed in the JDM literature that is not directly related to process tracing. Thus, process tracing methods clearly continue to be important research tools in the area of JDM. As expected, there is a recent increase in the number of papers measuring physiological and neural activity, but most other groups of process tracing methods also witnessed an increase in use. Relatively speaking, reaction time decreased its share over the years.

Counting (combinations of) keywords can only give an overall picture of a research endeavour. Much additional information is hidden in the details. We want to stress that our interest is the value of the methods as methods for uncovering cognitive processes, rather than as general research techniques. Pure numbers may be misleading in this respect. For instance, verbal protocols are nearly exclusively used for the goal of process tracing while methods measuring physiological or neural activity often have goals other than process tracing (as discussed earlier, a specific localization does not necessarily define a particular cognitive process). Therefore, the value of these techniques for process tracing is overestimated in the counting method that was used here. More detailed inspection of the papers within the groups is therefore necessary. However, our analysis helps articulate one of the main goals of the handbook: To summarize the scope and limits of scientific methods for process tracing when the methods have been developed as process tracing tools; to clarify the scope and limits of scientific methods for process tracing when the methods can be used for process tracing; and to develop features of existing methods in a way that they could be used for process tracing.

THEORIES BASED ON PROCESS TRACING METHODOLOGY

Some important models and theories in JDM owe their existence to the use of process tracing techniques. It is not an easy task to distinguish process models from other models, and we do not think that there is a straightforward way to do so. Nevertheless, some models are renowned because they make process predictions that have mainly been tested with process tracing techniques. We will briefly discuss some of these models.

Pennington and Hastie (1993) developed a story model of jury decision making, where the metacognitive feeling of having arrived at a coherent story is the central element for arriving at a verdict. Another model depicting decision making as a sequence of processes is the model of recognition-primed decisions (Klein, 1993). Most notably, there is no place in this process model for something like utility. Another process model is image theory

(Beach & Mitchell, 1987). These authors realized that the mechanisms that determine whether some option is admissible for a choice set is often more fundamental to decision making than the mechanisms that select the best option from that set. Still another process model is based on the idea that decision making consists of the search for a dominance structure (Montgomery, 1983). The key idea is that decision makers attempt to structure and restructure given information about options in such a way that one option becomes the self-evident choice. In a similar vein, Svenson (1992) developed 'differentiation and consolidation theory' which is mainly concerned with processes preceding choice (differentiation), and processes following choice (consolidation) rather than the choice result. Another process model was proposed by Huber (Huber, Beutter, Montoya, & Huber, 2001) for quasi-realistic risky choice scenarios. It is argued that many decision makers are not really interested in consequential information (on outcomes and probabilities) but rather are actively searching for risk-defusing operators. Finally, one of the most prominent among process models probably is decision field theory (Busemeyer & Townsend, 1993). Decision field theory is a dynamic approach to human decision making based on cognitive rather than economic principles. It models choice under uncertainty as a diffusion process; deliberation leads to variations in preference strength. This model predicts choice outcomes but, more importantly, also a wealth of process data, like response times, some context effects, serial position effects, speed - accuracy tradeoffs, changes in decisions under time pressure, and preference reversals.

All process models have in common that they propose that decision making is a stepwise process, with the choice being the penultimate, but not the central, stage. Although these models have gained some prominence in the decision theory literature, they have not made it to the top in terms of citations and influence. For an outsider to decision theory, this may be somewhat surprising, since these models – due to being much broader than utility theory – offer a much more nuanced and descriptive picture of the decision process than traditional utility theory and its variants. Three reasons may contribute to the relative neglect of these models: (i) that decision theory has its roots in economics, where the choice result is of central importance and where process models are unusual; (ii) that process data are often seen as weaker than input-output data; and (iii) that the handling of process data often demands advanced technology for data gathering as well as data analysis. The goal of the handbook is to show how some of the weaknesses and data handling problems of process tracing measures can be overcome.

GENERAL OBJECTIONS TO THE USE OF PROCESS TRACING METHODS

As is true for all methods of collecting data, process tracing methods suffer from drawbacks. First, process tracing methods are open to reactivity, either due to the delivery itself (e.g., in a thinking-aloud study) or due to the situation of recording (e.g., having electrodes attached to ones hand for recording GSR). Second, there is the problem of completeness in recording as well as in analysis. One has to decide on the specific features that are recorded (e.g., should filler words in verbal protocols be recorded?) and whether or not all recorded data are used in the analysis (e.g., there can be eye movements among those recorded that are due to extraneous influences and that therefore ought to be excluded). Third, these techniques often lack a systematic method for collection and coding, and sometimes also of analysis. Fourth, in order to enable unambiguous interpretation of the data the experimental setup needs rigorous control. Therefore, stimuli are often artificial and static. Most importantly, strong theoretical assumptions about the ongoing processes are required: there should be no process tracing without a clear model of the process.

The above drawbacks afflict the different methods to different degrees. The distinction between ‘subjective’ and ‘objective’ process tracing methods may be useful here. Subjective process tracing methods require that participants report upon mental contents that are available to themselves only. They have to have their ‘inner eye’ taking the record. That is, additional mental processes are necessary in order to register and express the target mental process in a proper manner. For instance, going back to our SEU example, a think-aloud study of risky choice may require that there is some activity, e.g., calculating the expected utility of prospects, and that participants are able to register this activity and to report verbally on it (e.g., by saying that they are doing a multiplication of outcomes with their probabilities). Similarly, when rating scales are used respondents need to be able to report on their mental contents and frequently also on metacognitive experiences (e.g., certainty or weight). For instance, if a participant says that an attribute ‘is important‘, she is actually reporting a metacognitive feeling whose source and validity is unknown.

In objective process tracing techniques no such additional activity is necessary. The registration and recording is done by a technical device that needs no additional process in order to observe the target process. For instance, if eye movements are recorded, there is no need for the participants to report on their eye movements. In our SEU example we would only register whether outcomes and their probabilities are fixated and whether at least one transition between them can be observed.

Clearly, the reservations against process tracing techniques differ between subjective and objective techniques. Reactivity, for instance is much more problematic in subjective techniques. Presumably, the more processing is influenced by top-down processes, the more reactivity is an issue. In thinking-aloud, top down processes in the form of folk psychological theories may be strongly activated (this is one of the main arguments of Nisbett & Wilson, 1977) and may bias both what one is registering of one’s own mental processes, and what one considers relevant for reporting.

A possible recipe for solving some of the problems associated with the use of subjective self-reports is the reliance on implicit measures. However, there is no strong evidence for the assumption that implicit measures are less susceptible to motivational effects of self-presentation, such as social desirability (Gawronski, LeBel, & Peters, 2007). More specifically, Gawronski et al. (2007) propose a model in which indirect measures provide a proxy for the activation of associations whereas self-reports are reflecting the outcome of validation processes.

Problems of reactivity in objective techniques are more on the general level of being an experimental participant, rather than relating to specific cognitive processes. It is open whether this is less critical, however. Take, as an example, an fMRI experiment of Goel, Buchel, Frith, and Dolan (2000) on the question of whether syllogistic reasoning is inherently a sentential linguistic process or a process requiring spatial manipulation and search. Given that syllogistic reasoning is hard work (even more when many syllogisms have to be solved) and that a scanner tube is a real noisy environment, there are grounds to suppose that these findings may not be unaffected by the experimental method.

The problem of completeness also raises different issues for subjective and objective techniques. If one has to report explicitly on one's mental processes, the most serious problem is that the report is incomplete. In fact, there will always be more processing than what is actually reported. For instance, a report of multiplication ("I did multiply") can be seen as indicating choice according to SEU. However, in a strict sense there is much more intermediary detail that needs to be demonstrated: that the result of the multiplication is memorized; that multiplication and memorizing is done for all prospects; that the memorized utilities are compared; and so on. Thus, presumably no subjective report will ever be complete. A specific feature of this problem is that it is possible that whole classes of cognitive processes fail to be reported. At different levels these are labeled differently; for instance there is the class of unconscious, implicit, holistic, system 1 thinking processes (Dijksterhuis & Nordgren, 2006); and there is the class of procedural representations. If so, subjective techniques offer a very limited window on the wealth of cognitive processes. Ironically, objective process tracing techniques face the opposing problem: they are over-complete. For instance, eye movements may indicate a step in a problem solving process, but they may also indicate something totally irrelevant to the process (e.g., saccades can become necessary because of biomechanical reasons, when, for instance, the eye has reached its maximum angle). Similarly, a scanning pattern going from an outcome to probability information may be indicative of calculating expected utility; at the same time it may also be indicative of a general left-right reading pattern. Thus, the trick is to distinguish meaningful from irrelevant observations.

With respect to the interpretation of the recorded observations, still other problems exist. Subjective techniques often lack a systematic method for registration and coding, frequently due to differences in problem content. As there is no problem-independent taxonomy of cognitive processes, a general coding scheme of the recorded observations does not exist. For objective process tracing techniques coding is not necessary. However, due to the wealth of data collected and due to the over-completeness of the data, there are also thorny problems of interpretation, e.g., what exactly determines a fixation in an eye-tracking study?

Finally, process tracing studies are often carried out in laboratory setups and under rigorous experimental control. This is especially true for objective techniques, since these techniques are often very sensitive. In addition, objective techniques (most notably the neural methods) frequently

need baseline control conditions for comparison. Therefore, well formulated theory is necessary to interpret such findings, and well formulated theory at the necessary level of detail often exists only for artificial tasks. Subjective techniques are not so vulnerable to this drawback, since they can be tailored specifically to the problem at hand. The wide use of thinking-aloud in the investigation of different areas of expertise is an example (Klein, Orasanu, Calderwood, & Zsambok, 1993; Ericsson, 2006). Page: 26
The chapters of the handbook give careful consideration and advice on these issues

SUMMARY AND CONCLUSION

This introductory chapter to the Handbook of Process Tracing Methods for Decision Research began with the story of Al the alien who realized that there are different approaches for understanding human decision making. The story shows how one could come up with a theory (as Al did in her first visit) of human decision making that is, in Popperian terms, scoring high as a good theory: it is easily testable and can therefore be falsified, it is fairly general, widely applicable, and makes new and surprising predictions while at the same time ruling out others. However, this theory ignores essential features of human decision making that are available to subjective experience. A theory on decision making must account for these experiences, and it must provide a way to model them.

Next, we provided a short characterization of process tracing methods in JDM research in Psychology. We discussed the most important among these methods, their merits and shortcomings. The goal of the handbook, however, is more ambitious than a simple description of existing process tracing techniques. Rather, it intends to contribute to the development of these techniques, because they are important and perhaps the only windows into the mind’s workings. What is necessary, however, before delving more deeply into the matter, is a diagnosis of the current state of affairs. This was the aim of the literature review part of the chapter. We ran a literature search of process tracing studies published in refereed journals over nearly 40 years. The results showed that there was a steady increase in process tracing papers. Thus, process tracing methods continue to be important research tools in JDM research. Given this rise in use of these techniques, it is of course necessary to maintain their quality, and if possible, to further develop them.

Process tracing is a basic approach of looking into the black box of cognitive processes it is in contrast to the structural research approach (Abelson & Levi, 1985) that relates choices to input variables. Structural approaches manipulate input variables and build statistical models to draw inferences *about the final decision*. Process tracing approaches on the other hand draw conclusions about *underlying psychological processes*.

Additionally cognitive representations are postulated that mediate between informational input and evaluative output. The changes that these representations undergo are observed since preferences are treated as resulting from these changes. Without the attempt to assess the psychological process at different stages from problem representation to final decision, any decision model will be incomplete. As is also convincingly argued in the final chapter of this handbook, process tracing methods are indispensable, if the goal is to shed some light into the black box.

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Figure Captions

Figure 1. Average hits for the different groups of methods within JDM research

Figure 2. Ratio of growth for the different groups of methods