Chapter 1

Theoretical Background

Newell and Simon's (1972) *Human Problem Solving* pioneered the application of the information processing approach to higher-order cognition. In their book, Newell and Simon introduced a list of important dimensions of human cognition which included a developmental facet. Unfortunately, this component received virtually no attention in this work: "The study is concerned primarily with performance, only a little with learning, and not at all with development or differences related to age" (Newell & Simon, 1972, p. 4). Mirroring Newell and Simon's seminal work, decision making researchers have largely neglected developmental change in cognitive function, including those changes due to aging. Consequently, and although the last 30 years have seen a major increase in the wealth of knowledge concerning decision making processes, our "current understanding of judgment and decision making in older adults is poor" (Peters, Hess, Auman, & Västfjäll, in prep; see also Peters, Finucane, Macgregor, & Slovic, 2000, Sanfey & Hastie, 1999, and Yates & Patalano, 1999). On the other hand, interest in the relation between decision making and development is growing (Peters et al., in prep). For example, Gigerenzer (2003) has argued that "one can study the ontogenetic change of the adaptive toolbox of *Homo heuristicus*" (p. 434). The main theoretical aim of this dissertation is to contribute to the study of the relation between ontogeny and higher-order cognition, in particular, the study of aging-related changes in decision making abilities.

This introductory chapter is structured in the following manner; first, I give an overview of research on cognitive aging. Second, I introduce the adaptive toolbox approach and point out its main contributions to the study of human rationality by discussing some paradigmatic examples of this research program. Third, I give an overview on the existing literature relating cognitive aging and decision making that provides the foundation for the work presented in the dissertation. Finally, I summarize some outstanding issues stemming from this review and highlight those that are addressed in the body of the dissertation.

Cognitive Aging: The Mechanics and Pragmatics of Cognition

Baltes (1987) has proposed a lifespan theory of intellectual development that views human ontogenesis as embedded in two streams of influence, the biological and the cultural

(Durham, 1991). As a consequence, the theory distinguishes between two main components of intellectual functioning: the mechanics and the pragmatics of cognition. According to Baltes and colleagues (Baltes, Lindenberger & Staudinger, 1998; Baltes, Staudinger, & Lindenberger, 1999), the mechanics of cognition are the expression of biological, genetically predisposed characteristics; in contrast, the pragmatics of cognition are assumed to be associated with acquired bodies of knowledge, being culture-dependent and experience based (see Figure 1.1).

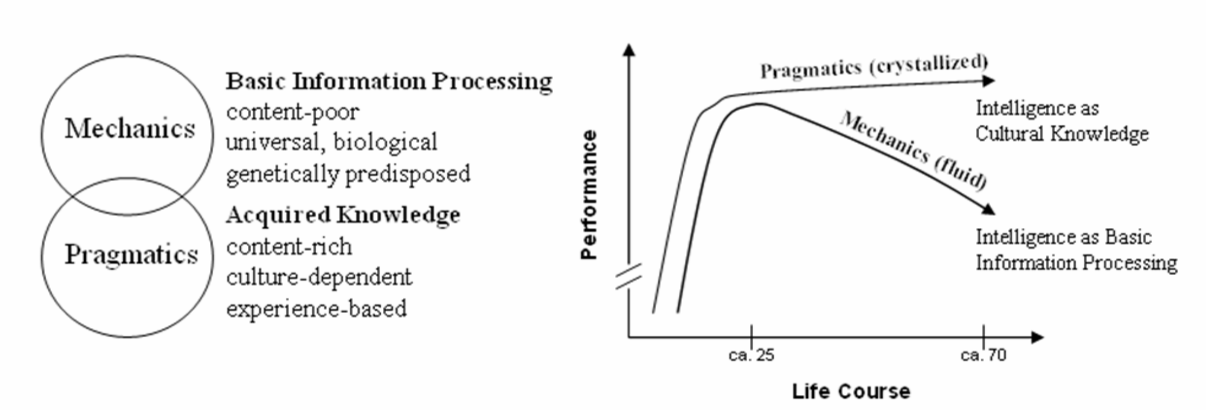

Figure 1.1: Fluid Mechanics and Crystallized Pragmatics. The figure on the left defines the two categories. The right panel illustrates postulated lifespan trajectories (adapted from Baltes, Staudinger, & Lindenberger, 1999)

The Two-Component Model of Intellectual Development (Baltes, 1987) draws on earlier formulations, such as the theory of fluid and crystallized intelligence (*Gf-Gc)* by Cattell (1971) and Horn (1982). These theories also hold that the two ability domains, *Gf* and *Gc*, have different age gradients, with fluid abilities, measured by tasks of inductive and deductive reasoning, being more vulnerable to age-related loss of brain efficiency compared to a more knowledge-based crystallized intelligence. Other theories that share with the two-component model the separation between two components of intellectual functioning include Hebb's (1949) proposal distinguishing intellectual power and intellectual products, and Ackerman's (1996) PPIK (process, personality, interests, and knowledge). This latter approach extends *Gf-Gc* theory by explicitly including personality and interests factors underlying motivational aspects of intelligence.

The major evidence that supports such a distinction between pragmatic and mechanic factors of intelligence is the difference between maintained and vulnerable intellectual abilities (Schaie, 1994). The Seattle Longitudinal Design (SLS; Schaie, 1994; Schaie & Willis, 1993) provides the most comprehensive set of data supporting this idea, including both cross-sectional and longitudinal analyses of cognitive aging. The cross-sectional findings indicated a steady decline in mechanic abilities such as inductive reasoning, perceptual speed, spatial orientation, and verbal memory, whereas the more crystallized numeric and verbal abilities seemed to peak during middle adulthood and show little or no decline up to about age 70. The longitudinal findings of the SLS show more uniform shapes for the different abilities and less decrement with aging than the cross-sectional data but, overall, the main distinction between maintained and vulnerable intellectual abilities is supported. Another study, the Berlin Aging Study (BASE; Baltes & Meyer, 1999), showed similar age gradients: cross-sectional data indicated that abilities that involve mechanics, like perceptual speed or spatial orientation, show decline during adulthood and acceleration of decline in very old age; pragmatic abilities, such as verbal knowledge show weak decline or some decline only in very old age. Longitudinal analysis showed similar patterns (Singer, Verhagen, Ghisletta, Lindenberger & Baltes, 2003). In sum, both cross-sectional and longitudinal findings seem to suggest the existence of different age-gradients associated with the mechanics and pragmatics of cognitive functioning. In what follows, these two components are analyzed further.

The Mechanics of Cognition

Baltes, Staudinger, and Lindenberger (1999) proposed that the mechanics of cognition reflect fundamental properties of the central nervous system and that these are indexed by three basic cognitive functions: information processing rate (Salthouse, 1996); working memory capacity (Baddeley, 1986); and inhibition-related functions (Zacks & Hasher, 1997).

Speed of Processing

The speed of processing theory (Salthouse, 1985, 1996) tries to account for the ubiquitous finding that cognitive performance slows down with increasing age (Cerella, 1985). At a neurological level the theory holds that processing speed of neuronal operations lead to differences in basic cognitive function (cf., Meyerson, Hale, Wagstaff, Poon, Smith, 1990). At an information processing level, the theory states that with aging relevant operations are executed too slowly to be completed in available time (limited time mechanism), particularly when there are external time limits or other restrictions on time of processing. In addition, it is assumed that slow processing reduces the amount of information simultaneously available for higher level processing (simultaneity mechanism). Correlational analyses with mediational models have shown measures of speed to be good predictors of age-associated variance in several measures of memory and reasoning (see Salthouse, 1996, for a review).

Working Memory and Short-term Memory

Working memory refers to a system or mechanism for temporarily maintaining information needed during the execution of a cognitive task (Baddeley, 1986). A more precise and yet consensual definition is hard to come by due to the controversial status of the construct (Shah & Miyake, 1999) and the many research areas it involves (Neath, Brown, Poirier, & Fortin, 1999). There have been attempts to sketch a picture of what sort of components constitute working memory and how they interact at the verbal-conceptual (e.g., Baddeley, 1986), computational (e.g., Lovett, Reder, & Lebiere, 1999), and neural levels (e.g., Smith & Jonides, 1997). Although there is some disagreement about the specific characterization of these systems, most current views stipulate that working memory consists of storage mechanisms that keep a limited amount of information active for a brief period of time, and executive processes that manipulate and code the stored information in the service of higher cognitive demands (Miyake & Shaw, 1999). Some authors have argued that this storage and processing distinction resides at the heart of the difference between working memory and short-term memory; working memory being the resulting combination of the workings of a storage component or short-term memory, plus an attentional component or central executive (Engle, Tuholski, Laughlin, Conway, 1999).

Aging-related decline in working memory has been found in many memory span tasks (Craik & Jennings, 1992; Park et al., 1996). One issue regarding these findings is whether this decline occurs mostly for storage or processing operations. In general, reliable age differences have been reported between memory tasks that emphasize storage and those that emphasize storage plus executive processing operations (see Hasher & Zacks, 1988, Hess, 2005, for reviews). For instance, Dobbs and Rule (1989) found that age did not predict performance on forward and backward digit span tasks. However, in a N-back task age differences were pronounced and age predicted performance. Similarly, Verhaegen, Marcoen, and Goessens (1993) found that the effect size of age differences associated with tasks that contain both a processing and storage component (d = .81) was larger than that with tasks with minimal processing demands (d = .48). In sum, although age effects have been found for both storage and processing components of memory, the latter seem to be particularly affected as a function of age.

Inhibiton-related Functions

The notions of inhibition and interference are associated with abilities such as the capacity to disregard irrelevant information when solving a particular task, or the ability to deliberately suppress dominant, automatic responses. However, the large number of paradigms used in the research on inhibition and interference often reveal inconsistent findings (see McDowd & Shaw, 2000, for a review) and, accordingly, different definitions of these concepts abound (cf. Friedman & Myake, 2004).

Deficits in inhibition-related functions have been proposed as an explanation for differences in performance between younger and older adults (Andrés, van der Linden, & Parmentier, 2004; Hasher & Zacks, 1988), namely, age-related decrements in Stroop and proactive interference tasks (Zacks, Hasher, & Li, 1999). However, some research has failed to find inhibitory deficits in elderly subjects (Mayr, 2001). Thus, although there is some evidence that the notions of inhibition and interference may be important in understanding cognitive aging, further research and theoretical integration is necessary.

The Relation between Components of Mechanics of Cognition

Some researchers have equated fluid intelligence with particular components, such as working memory (Kyllonen & Krystal, 1990). Other authors have argued that the different constructs described above, speed, working memory, and inhibition-related functions, have important, non-negligible relations (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Kane & Engle, 2003; Salthouse, 1996; Salthouse & Babcock, 1991), or even that they are conceptually interdependent, sharing basic, neurological modulation processes (Li, Lindenberger, Sikström, 2001). Although these ideas are alluring in that they attempt to provide a more parsimonious picture of the components of cognition, there is abundant evidence that these are separate constructs with different predictive value (Ackerman, Beier, & Boyle, 2002; Conway, Kane, & Engle, 2003; Engle et al. 1999; Süß, Oberauer, Wittmann, Wilhelm, Schulze, 2002). However, given the discordant opinions and empirical findings concerning the relation between some of these constructs it is wise to consider the role of all these components in higher-order cognition. Furthermore, it remains an empirical question how well these different components predict the use of decision strategies and age differences in decision behavior. One of the goals of the work presented here will be to investigate the relation between these different components and age differences in decision making abilities.

The Pragmatics of Cognition

The concept of pragmatics of cognition reflects the acquisition of culturally transmitted knowledge, which can be of procedural as well as of declarative nature. Some of the acquired bodies of knowledge are normative, such as those provided by formal schooling, while others are more idiosyncratic and associated with expertise.

Normative Pragmatic Knowledge

Age differences in normative pragmatic knowledge are well captured by standard psychometric testing procedures (Baltes, Staudinger, & Lindenberger, 1998). These testing methods purportedly measure how individuals invested cognitive potential into culturally valued bodies of knowledge which are then well preserved throughout the lifespan. Typical examples of these include reading and writing skills, but also general everyday problem-solving abilities. A paradigmatic measure of such pragmatic knowledge is vocabulary, that is, the number of words one knows, which peaks in adulthood and is relatively well-maintained until very old age (Schaie, 1996).

Person-Specific Pragmatic Knowledge

Researchers have tried to identify the effects of domain-specific knowledge by comparing the performance of younger and older experts and novices both inside and outside their domain of expertise. The main conclusion of this line of work is that expertise effects rarely transcend the boundaries of the specific domain. For instance, basic cognitive mechanics, such as speed, are not altered through extended practice (Salthouse, 1991). Additionally, expertise does not provide a complete safeguard from aging effects in the domain of expertise (Krampe & Ericsson, 1996; Lindenberger, Kliegl, & Baltes, 1992).

Successful Aging: Selective Optimization with Compensation

Human cognitive aging has been traditionally conceptualized as representing a universal decline in psychological functioning. In truth, one could easily arrive at such a view from considering the age-gradients described above, with performance in measures of mechanics declining throughout adulthood and performance in pragmatics declining during old or very old age. Nevertheless, another standpoint is gaining ground which views cognitive aging as a combination of gains and losses in function, albeit one involving more losses than gains (Baltes & Singer, 2001).

This view of development is particularly well represented in the selective optimization with compensation (SOC) model proposed by Margret Baltes, Paul Baltes, and collaborators (Baltes & Baltes, 1990; Baltes & Carstensen, 1996; Freund & Baltes, 1998). The model can be seen as a metatheoretical framework for understanding development in different periods of the life span, including childhood and old age. This framework sees successful regulation of life span development as resulting from the interaction of three developmental-regulatory processes: selection, optimization, and compensation. *Selection* concerns the processes of consciously or unconsciously choosing actions or goals from an available set. One example of this type of process is choosing a course of studies based on personal motivations and abilities as well as majors available. Researchers have found it useful to distinguish between elective selection, a motivation-driven selection from a number of possible alternatives (“I really want to study math, so I will be a science major”), and loss-based selection, which results from the unavailability of resources (“My math skills are so poor, I should be a humanities major”). *Optimization* refers to the acquisition, refinement, and coordinated application of resources directed at achieving the desired goals. Finally, *compensation* addresses the regulation of loss in development, corresponding to the effort to maintain a given level of functioning despite decline of previously available resources. Compensation represents an alternative to loss-based selection because it implies reorganization around the loss.

According to the SOC framework, *successful aging* involves the selection of actions that given the current personal resources and environmental demands fulfill a coordinated goal-directed plan. The example of Arthur Rubenstein, as an 80-year-old pianist, is illustrative (cf. Baltes, Staudinger, & Lindenberger, 1999). When asked how he maintained such a high-performance well into old age he mentioned three strategies. First, he played fewer pieces (selection); second, he practiced these pieces more often (optimization); finally, to make up for his loss in mechanical speed, he played more slowly before fast segments to make these appear faster (compensation). Supporting this anecdotal evidence for the successful use of the processes of selection, optimization, and compensation, Freund and Baltes (1998) have found that people using SOC strategies report higher levels in subjective indicators of successful aging.

Summing up, the general idea that cognitive resources decline with age leads to a negative view of development concerning the later period of the life span. Nevertheless, the SOC framework hints that successful aging is possible through the coordinated employment of compensatory strategies that can to some extent counteract age-related cognitive decline and depletion in environmental resources. The orchestration of gains and losses is thus a crucial aspect of theories of successful aging. Decision making is an appropriate area for studying the developmental dynamics of gains and losses in intellectual functioning because abilities underlying decision making are the result of the interplay between basic biological components of cognition as well as acquired bodies of knowledge. Moreover, the decision making domain is open to to examination of how individuals adapt their strategy use as a function of changes in different components of intellectual functioning. Hence, studying age-related changes in decision making abilities provides an ideal test bed for theories of successful aging.

In the next section I provide an overview of the decision making framework that guides the work presented in this dissertation.

The Adaptive Toolbox Approach

From Bounded to Ecological Rationality

The adaptive toolbox approach (Gigerenzer, Todd, & the ABC Research Group, 1999; Gigerenzer & Selten, 2001) is a research program primarily concerned with higher-order cognition, in particular, decision-making. A main idea that guides this approach is that of *bounded rationality*. Simon (1957) introduced the bounded rationality framework as an attempt to investigate how cognitive systems solve the problems they are faced with in an efficient manner given constrains in available resources (e.g., time, computational power). This idea of bounded rationality is deeply associated with the thought that cognitive systems are fundamentally adapted to their environments – Simon illustrated this idea with a metaphor: mind and environment as blades of a pair of scissors. The intuition that cognition and environment are deeply intertwined has led the adaptive toolbox approach to defend a particular solution to the problem of how bounded rational beings can behave adaptively: *Ecological rationality*. The principle of ecological rationality proposes that specific simple cognitive mechanisms can achieve good performance by exploiting the structure of an environment in which they operate, in other words, if they let the environment do some of the work. From this stems the suggestion that organisms will profit from having a repertoire of tools that fit specific environments and therefore allow them to perform adaptively on the whole.

Ecological Rationality: Precursors and Related Theories

The degree to which mechanisms of the mind can be understood without full consideration of their environmental context is a key concern within the cognitive sciences. The concept of ecological rationality adopted by the adaptive toolbox program addresses this concern by considering the degree of fit between a mental mechanism and an environment. However, one must acknowledge several pioneering contributions to this vision of rationality. As discussed above, Herbert Simon (1956, 1957) saw mind and environment as two blades of a pair of scissors. Egon Brunswik (1955: cf., Dhami, Hertwig, & Hoffrage, 2004) argued that psychological processes are adapted to environmental properties; James Gibson (1979) tried to enumerate invariant features of the environment while postulating little structure on the mind; Roger Shepard (1987) spoke of the evolutionary internalization of universal regularities in the world, such as abstract features based on geometry, probability, as well as physical properties of objects. All these approaches have in common their focus on environmental structure and its relation to cognition.

Furthermore, several other contemporary approaches have made claims about the importance of a focus on environmental structure and some have particularly mentioned the importance of understanding the fit between mind and environment. Evolutionary psychology (e.g., Barkow, Cosmides, & Tooby, 1992) has analyzed the differences between past and present environments and argued that properties of mechanisms were shaped through evolutionary processes to be functional in ancestral environments. Also, albeit putting less emphasis on evolutionary processes, the rational analysis of thought (Anderson, 1990; Chater & Oaksford, 1999; Schooler & Anderson, 1997) has made claims about how regularities in information processing are fundamentally related to statistical regularities of the environment.

The fundamental importance of the environment has also been explored by other authors who consider the exploitation of environmental structure as a major feature of the cognitive system (Clancey, 1997; Clark, 1997, 1999; Agre & Chapman, 1987). Exploitation may take form in the use of cheap cues, active sensing, or repeated environmental consultations. Hutchins (1995a; 1995b) takes a similar route by viewing a problem solving task as a computational system, only a subset of which can properly be regarded as residing "within the skin" of the cognitive system. A related debate concerns the role of representation within cognitive architectures (Markman & Dietrich, 2000; Brooks, 1991), with some arguing that simpler and fewer representations are needed if one allows the cognitive system to consult an information rich environment, thus, lessening the requirement for complex models of the world. Simpler representations such as these would imply the occurrence of phenomena like change blindness, that is, the inability of individuals to detect major changes in their surroundings (but see Simons & Rensink, 2005). Further examples emphasizing the importance of environmental structure for cognition include the role of linguistic information present in the environment during language acquisition (Elman, 1990, 2005; Christiansen & Chater, 1999; Eisner, 2002) and its evolution through repeated cultural transmission (Christiansen & Kirby, 2003).

Main Theoretical Contribution of the Adaptive Toolbox Approach

All of the approaches cited above are closely related in spirit to the adaptive toolbox approach focus on the fit between mind and environment. The major distinguishing feature between these approaches and that of the adaptive toolbox program is the claim that *the fit between mind and environment allows mechanisms to be both simple and successful*. The adaptive toolbox approach contends that because simple mechanisms are tuned to specific characteristics of natural environments they can match or exceed the predictive accuracy, speed of traditional models of inference that ignore environment structure (e.g., Von Neumann & Morgenstern, 1944). Underpinning this research is the metaphor that the cognitive system relies on an adaptive toolbox of simple mechanisms. These simple mechanisms sidestep the need to postulate psychologically implausible conceptions of rationality requiring unlikely levels of knowledge and computational resources (Gigerenzer & Selten, 2001). A model of mind based on an adaptive toolbox is therefore boundedly rational in the sense of relying on realistic levels of mental resources, and is ecologically rational in the sense of being tuned to characteristics of natural environments.

The Contents of the Adaptive Toolbox

Which devices reside in the adaptive toolbox? One very general answer to this question is: those mechanisms that allow humans to function in their environments. Given this premise one would want to consider evolutionary psychology's insights into what should be considered central problems for the human species during evolutionary time. Buss (1999) has proposed foraging, mating, parenting, and cooperation as major areas in which humans faced reoccurring problems with similar structure over philogenetic time. According to evolutionary thought (Cosmides & Tooby, 1987) one would expect to find domain-specific mechanisms tuned to the particulars of specific problems within these classes. In fact, such domain-specific mechanisms have been proposed in different domains, such as rules of thumb for foraging behaviour (Wilke, Hutchinson, & Todd, 2004); heuristics for mate-search (Simão, Todd, & Billari, 2005); allocation strategies for parenting (Hertwig, Davis, & Sulloway, 2002), and rules of conduct for cooperative behaviour (Axelrod & Hamilton, 1981).

Still, the extent to which the mind is composed of modular mechanisms has been the focus of intense debate (Samuels, 1998; Fodor, 2000; Sperber, 2002). Moreover, most of the strategies considered in the decision making literature are not domain- but task-specific (Carruthers, in press), that is, they can be applied to any domain, but are constrained in the type of task they can be applied to. For example, consider the Take The Best heuristic described above, TTB can in principle be applied to any stimulus category, and people have been reported to use it in different domains of inference, such as stock options' performance (Bröder, 2003), criminal offence (Bröder & Schiffer, 2003), toxicity of bugs (Juslin, Jones, Olsson, & Winman, 2003), and the salary of individuals (Rakow, Hinvest, Jackson, & Palmer, 2004). Nonetheless, all of these examples have in common that they refer to paired comparison tasks to which TTB can be applied.

In sum, there have been two main approaches to uncovering which strategies populate the adaptive toolbox. One has been to look at relevant problems which are likely to have reoccurred during philogenetic time and postulate mechanisms that could have provided good solutions to these. Another approach has been to consider important tasks in present environments and propose plausible strategies to handle them. Both approaches involve processes of inference and empirical testing. First, a mechanism is inferred or hypothesized from considerations of the environmental and task structures and, second, the existence of such a mechanism is put to a test using available experimental procedures. The multitude of potential tasks and mechanisms that could be analyzed makes the endeavor of outlining the contents of the adaptive toolbox a particularly taxing one. In the next section I present an overview of work that aimed at uncovering the contents of the adaptive toolbox and understanding the link between particular environments and precisely detailed cognitive mechanisms.

Testing the Fit: Examples of Ecological Rationality

The adaptive toolbox program strives to identify different types of environmental structures in terms of quantifiable statistics and propose simple mechanisms that take advantage of such structures to make correct and efficient decisions. The following paragraphs give an overview of analytical and simulation work analyzing the fit between environments and simple mechanisms, as well as a summary of empirical research on people's use of the posited mechanisms.

Profiting from Systematic Distribution of Ignorance: The Recognition Heuristic

One type of environment that has received attention is that in which the probability of observing an object is correlated with some of its characteristics. For instance, the probability of a city name appearing in a newspaper article is correlated with cities' population size. Given the task of determining which of two objects scores higher on a criterion, such as which of two cities has more inhabitants, can a simple mechanism exploit this statistical property? Goldstein and Gigerenzer (2002) calculated the success of a simple algorithm that uses only recognition information – the recognition heuristic - in 10 environments (e.g., city sizes, mountain height) and found that it did astoundingly well. Borges, Goldstein, Ortmann, and Gigerenzer (1999) showed that the recognition heuristic can be very successful at picking high-performing companies in a bull stock-market. Recognition will be informative whenever the occurrence of events is systematically associated with the objects' characteristics, in other words, when ignorance is systematic. Furthermore, Gigerenzer and Goldstein (2002) have demonstrated a *less-is-more effect*, where someone using the recognition heuristic and possessing less than full knowledge (only recognizing some objects) can make more correct decisions than someone who recognizes more objects.

Single individuals and individuals in group settings have been shown to act in accordance with the recognition heuristic (Goldstein & Gigerenzer, 1999, 2002; Reimer & Katsikopoulos, 2004). Current research has focused on whether the use of the recognition heuristic is noncompensatory in nature (Oppenheimer, 2003), the status of recognition compared to other cues (Bröder & Eichler, submitted), and how other related information, such as fluency, can be used in a similar manner (Schooler & Hertwig, 2005).

Noncompensatory Environments: The Take The Best Heuristic

A noncompensatory environment is one in which each single cue cannot be outweighed or outvoted by any combination of less important cues. Take The Best (TTB; Gigerenzer, Hoffrage, & Kleinbölting, 1991; Goldstein & Gigerenzer, 1996) is a simple lexicographic heuristic for forced-choice pair-comparison tasks that can profit from such a distribution of cues. The performance of TTB has been compared to different types of models, including exemplar based models (Juslin & Persson, 2002), connectionist networks (Chater, Oaksford, Nakisa, & Redington, 2003), linear models (Martignon & Hoffrage, 2002), bayesian nets (Martignon & Schmitt, 1999). Overall, TTB's combination of accuracy, frugality, simplicity, and robustness is impressive but both TTB and other models' success seem to crucially depend on the type of environment (Gigerenzer, Czerlinsky, & Martignon, 1999).

Current empirical research has focused on the conditions that determine people's adherence to TTB such as the cost of information relative to its utility (Bröder, 2000, 2002; Newell & Shanks, 2003), number of cues (Newell, Weston, & Shanks, 2003), type of task (probabilistic vs. deterministic; Newell & Shanks, 2003), time pressure (Rieskamp & Hoffrage, 1999), information format (Bröder & Schiffer, 2003a) cognitive capacity (Bröder, 2003; Bröder & Schiffer, 2003b), and richness of feedback (Juslin, Jones, Olsson, Winman, 2003). Other simulation and empirical work has focused on the learning of cue orders required by TTB (Newell, Rakow, Weston, & Shanks, 2003; Dieckman & Todd, 2004).

Friendly and Unfriendly Environments: One-reason Decision Making in Preferential Choice

Shanteau and Thomas (2000) proposed a distinction between "friendly" choice environments, in which attributes agree rather than conflict in terms of the choices they support, and "unfriendly" environments, in which trade-offs need to be made between conflicting attributes. Fasolo, McClelland, and Todd (in press) used simulations to study how consumers can make good choices in environments differing in their "friendliness" (i.e., inter-cue correlation). Their simulations showed that considering less than full information (i.e., number of cues potentially available) has the benefit of leading to lower proportion of non-dominated options, thus reducing choice conflict. Furthermore, they showed that the costs of considering fewer options can be low: the proportion of value lost when using just one attribute is small if attributes are positively correlated. Only in unfriendly environments and when cues were assigned equal importance was extensive cue search needed to choose an object that was not significantly inferior to the best option.

The Bigger-is-rarer Property of J-shaped Environments: The QuickEst Heuristic

The ubiquity of power law distributions is impressive: Different environments, from the size of animal species (Schroeder, 1991) to the degree of node connectivity in social and communication networks (Faloutsos, Faloutsos, Faloutsos, 1999) are best described as power, J-shaped, distributions. This distribution reflects a bigger-is-rarer property: few objects have very large values and a vast majority of objects possess small ones. For example, few cities have very large populations but the majority has relatively few inhabitants. Hertwig, Hoffrage, and Martignon (1999) have proposed a fast and frugal strategy that exploits the bigger-is-rarer property, QuickEst, a heuristic for estimating quantities such as the population of cities. QuickEst's performance has been tested against a variety of models including exemplar based models (PROBEX; Juslin & Persson, 2002; Persson & Juslin, 2000) and a number of linear models (Juslin & Persson, 2002; Hertwig, Hoffrage, & Martignon, 1999). Overall, QuickEst does well compared to other models and proves particularly frugal. Research is just beginning on people's use of QuickEst and other heuristics that can exploit J-shaped structures (Hausmann, Läge, Pohl, & Bröder, submitted)

Quo Vadimus?

The brief tour through some of the efforts at uncovering the relation between environment and the success of simple mechanisms has shown that the scope of the adaptive toolbox approach is broad. The reach of this dissertation however is less ambitious as it will consider a particular problem – *deciding between options* – and investigate the issues of interest only with respect to this domain. The decision making field has devoted considerable attention to the problem of choosing between alternatives, however, very little is known concerning the relation between aging and inference processes in this area. Consequently, in an attempt to fill this gap, the focus of the work will fall on decisions between options, the strategies that have been proposed to handle these problems, and, later on, the changes that may occur in these processes over the life span.

Extending the Metaphor: Selecting vs. Applying Tools

The metaphor of an adaptive toolbox is extremely useful in conveying the idea that individuals have at their disposal a multitude of strategies. However, it will be useful to extend this metaphor further and consider two issues that surface when considering the use of decision strategies. The first issue concerns strategy selection, which represents the idea that to use a particular tool one needs to select it from the available set of devices in the toolkit. Second, given that one has decided on a particular tool, it is necessary to operate it, handle it in an appropriate manner to fulfill one's goal – the issue of strategy application. The main idea captured by this image is that there are different processes to be studied concerning (1) how adaptive one is in choosing a strategy as a function of one's own resources and the characteristics of the challenge at hand, and (2) how effectively one can use a particular strategy once it has been selected.

This conceptual partition is compatible with both Logan's (1985) and Siegler and Lemaire's (1997) distinction between choosing a strategy and implementing it. Moreover, it points out that there is no reason to assume that these abilities are equally susceptible to the effects of advancing age. In accordance with this view, Salthouse (1991) has acknowledged the possibility of differential age-related changes in these two aspects of strategy use by advancing two distinct hypotheses, 1) the production deficiency hypothesis, which states that younger adults choose strategy more adaptively than older ones, and 2) the processing deficiency hypothesis, which assumes that choices of strategies are equally adaptive for the two age-groups but that younger adults execute strategies more effectively compared to older ones. In short, differentiating between strategy selection and strategy application seems a crucial step to understand strategy use and, in particular, associated age-related changes in this respect. Consequently, this distinction will guide the rest of the theoretical introduction as well as the overall structure of the thesis.

Strategy Selection

When considering how people select a tool from the adaptive toolbox at least two main questions arise: Which tools are available in the toolkit? What factors influence the choice of tools? The next sections provide partial answers to these questions by giving an overview of 1) strategies that have been proposed to decide between alternatives on the basis of a set of cues or attributes, 2) the most prominent models of strategy selection, and 3) what is know about the impact of task and individual characteristics on the use of decision strategies. Additionally, one outstanding issue which provides considerable thrust for the work reported in this thesis is introduced, namely, the failure of current decision making theories to account for the role of individual characteristics in strategy selection.

Decisions between Options: Multi-alternative, Multi-attribute Decision Making

Researchers have identified a number of decision strategies that can be used in tasks involving a choice between alternatives and in which a set of cues is available (Abelson & Levi, 1985; Alba & Mamorstein, 1987; Fishburn, 1974; Huber, 1980; Luce, 1959; for a review see Svenson, 1983). Some of these strategies are presented in Table 1.1. The list presented is far from complete because rather than providing a systematic review of strategies the list aims at illustrating a point: Different proposed algorithms make use of diverse types and quantity of information. A particular decision problem usually contains information concerning several attributes or cues on each alternative, as well as the predictive value or validity associated with each cue. However, different strategies make differential use of this information, with some, like Franklin’s rule, fully integrating cue values and their validities, and others, using them only to guide search or ignoring cue validities altogether, like TTB and Tally, respectively. Nevertheless, these strategies also have commonalities, for instance, Tally and Franklin’s rule do not have a stopping rule, that is, a mechanism that determines when search should be stopped, thus, they always use all cue values to make a decision. In contrast, TTB, EBA, and Take Two all have stopping rules that makes them neglect part of the information.

A common distinction made in the decision making literature is that between compensatory and noncompensatory strategies. A compensatory strategy allows tradeoffs among attributes so that a value on one cue can be compensated by a combination of less important ones; Franklin’s rule is such a strategy. In contrast, a strategy like TTB is noncompensatory, operating in such a way that a cue cannot be outweighed by any combination of less important cues.

Table 1.1: Decision Making Strategies

Strategy	Description
Take The Best (TTB) (Gigerenzer, Hoffrage, & Kleinbölting, 1991)	TTB is a strategy for multiple-cue pair-comparison tasks. TTB looks up cues according to a descending rank-ordering based on validity. Validity is defined as the proportion of right inferences a cue supplies (Gigerenzer & Goldstein, 1996). To make a decision TTB selects the alternative with the highest value on the cue with highest validity. If the two alternatives have the same value, the cue with the second highest validity is considered, and so on.
Take Two (Dieckmann & Rieskamp, in press)	Like TTB, Take Two looks up information by ranked validity. However, Take Two makes a decision as soon as it finds *two* pieces of discriminating evidence favoring a particular alternative.
Elimination-by-aspects (EBA, Tversky, 1972)	Elimination-by-aspects eliminates all alternatives that do not exceed a specified value on the cue with the highest predictive value. If more than one alternative remains, the second best cue is selected, and so on.
Tallying (Gigerenzer & Goldstein, 1996)	The additive strategy calculates for each alternative the sum of the cue values and selects the alternative with the highest score.
Franklin's rule (Gigerenzer et al., 1999)	Franklin's rule calculates for each alternative the sum of the cue values multiplied by the corresponding cue validities and selects the alternative with the highest score.

Models of Strategy Selection

Contingency models of strategy selection. Simon (1956) argued that to understand cognition one must take into consideration both task demands and decision makers' resources. Beach and Mitchell's (1978) contingency model and Payne, Bettman, and Johnson's *Adaptive Decision Maker* approach (1988; Bettman, Johnson, & Payne, 1990) share this concern. These theories of strategy selection are based on the assumption that people have a repertoire of strategies that can be evaluated in terms of their costs and benefits. The costs are assumed to be related to the cognitive effort necessary to apply a strategy while the benefits are related to its accuracy. According to this view, the decision maker anticipates, although not necessarily consciously, the effort and accuracy of a strategy and uses these criteria to select the best one for the particular decision problem. These theories see strategy selection as being contingent on both the characteristics of the decision task and the decision maker. Consequently, one main goal of these approaches has been to show that people can skillfully adapt their strategy use as a function of different task demands (e.g., costs of information, available time; e.g., Payne, Bettman, & Johnson, 1988, 1993). Comparatively, and as will be shown below, little work has been done on the role of individual characteristics in determining strategy selection.

Strategy selection learning model. Busemeyer (1993) has criticized the contingency models presented above (Beach & Mitchell, 1978; Payne, Bettman, & Johnson, 1988) because they are not explicit in defining precisely how the trade-off between costs and benefits works at a computational level. One attempt aimed at dealing with this critique, the strategy selection learning (SSL) theory (Riesakmp & Otto, submitted), has proposed that "people do not consciously select strategies according to their effort and accuracy but learn to select appropriate strategies" (p. 4). SSL assumes that individuals use subjective expectancies associated with each strategy and select strategies proportional to these expectancies which are updated on the basis of experience. In several studies these authors have shown that, in line with their model's prediction, individuals are able to change strategies as a function of feedback. Undoubtedly, this proposal represents an important step in the direction of formalizing theories of strategy selection. However, its major strength lies in explaining learning which strategy to use on the basis of extensive feedback, leaving still open how strategy selection works in those situations where feedback is not available and how other factors, such as individual characteristics, contribute to the selection. The next sections review the research on how characteristics of decision problems and of decision makers determine which strategies are picked from the toolkit.

The Characteristics of the Decision Problem and Strategy Selection

Number of alternatives and attributes. Having a large number of alternatives to decide upon has been shown to lead people to adopt noncompensatory heuristics (e.g., Ford, Schmitt, Schechtman, Hults, & Doherty, 1989; Payne, 1976; Payne, Bettman, & Johnson, 1988; Rieskamp & Hoffrage, 1999). Mixed findings have been reported regarding the effect of the number of cues. Payne (1976) did not find that a larger number of cues made people adopt noncompensatory strategies; Sundstrom (1987), however, did. Interestingly, Newell, Weston, and Shanks (2003) found that the number of people that could be categorized as using noncompensatory strategies was actually higher when fewer cues were available. Newell et al. interpreted this finding as reflecting people's attempts at uncertainty reduction when many cues were available as opposed to only two. These results stress that these experiments must be interpreted within a framework that considers not only the properties of the task but also the decision makers characteristics, such as their expectations about the task.

Time pressure. Payne, Bettman, and Johnson (1988) provided some support for the idea that simple strategies may be particularly useful and accurate in situations where little time is available for making a decision. In line with this view, it has been shown that time pressure leads decision makers to rely more on simpler, noncompensatory decision strategies (Payne, 1976; Payne et al., 1988; Rieskamp & Hoffrage, 1999; see Svenson & Maule, 1993, for a review).

Information costs. Several researchers have shown that increased costs of information search lead to the use of noncompensatory strategies such as TTB (Bröder, 2000; Newell et al., 2003; Newell & Shanks, 2003).

Structure of cue validities. One of the main points of the adaptive toolbox approach is that simple strategies can outperform more complex ones given the proper environment. For instance, it has been shown that, depending on the environmental structure, TTB's predictive performance can equal or exceed that of sophisticated machine learning algorithms (Brighton, in prep.; Martignon & Hoffrage, 1999). Thus, the structure of the environment should be crucial in determining strategy use. Accordingly, the effect of some environmental characteristics on strategy use has been studied. For instance, Bröder (2003) has recently evaluated strategy use in two different environments, a compensatory and a noncompensatory one. Bröder reported that people behaved adaptively, using TTB significantly more in the noncompensatory than in the compensatory environment (56% and 26% respectively). Similarly, Bröder (2000, experiment 2) showed a small difference in the use of simpler strategies in a high vs. low cue validity dispersion environment. Karlsson, Juslin, and Olsson (2003) have also gathered some data that seem to imply that people can use different strategies depending on the structure of the environment. According to the authors, while an additive environment (i.e., where the criterion is a linear additive function of the cues) allows for people to use a rule-based process to make decisions, a multiplicative one (i.e., where the criterion is a multiplicative function of the cues) is too demanding for a rule extraction process, thus requiring a less effortful exemplar-based decision process based on similarity.

Inference from givens vs. inference from memory. Another major determinant of strategy use seems to be the nature of the demands the task makes on the decision makers' cognitive system. Gigerenzer and Todd (1999) have distinguished between tasks that require inferences from givens and those requiring inferences from memory. Although both types of inferences require search for information, it is reasonable to expect that the processes underlying performance in the two types of task differ. Gigerenzer and Todd (1999) proposed that information search in memory should trigger the use of simple heuristics because this search implies greater cognitive costs compared to the typical information board paradigm. Bröder and Schiffer (2003) have investigated the issue and, as predicted, found that people rely more on a simple lexicographic rule when faced with a task where they have to recall information from long-term memory than when this information is displayed on a screen.

Summing up, three main conclusions can be gleaned from this overview of the role of task characteristics on strategy use. First, the decision making literature shows that increased task demands (e.g., little time available, information search in memory) increases the use of simpler, less computationally demanding strategies. Second, the statistical properties of environments such as dispersion of cue validities influence people's choice of strategies such that individuals adapt their strategy use to achieve better performances in particular environments. Finally, there appears to be a relation between task characteristics and the resulting demands imposed on the decision maker, suggesting that to understand decision behaviour one must take into consideration not only task structure but also the characteristics of the cognitive system.

The Characteristics of the Decision Maker and Strategy Selection

The idea that cognitive capacity is a major determinant of strategy use is evident in the bounded rationality framework. Herbert Simon, for example, stated that "limitations such as those of short-term memory are fundamental" (Baars, 1986, p. 363). In studies of higher-order cognition involving complex tasks, such as air traffic control, individual differences in reasoning ability and working memory have been found to be correlated with strategy adaptivity (Schunn & Reder, 2001; see Schunn, Lovet, & Reder, 2001, however, who failed to find the effect of working memory with other tasks). Also, Stanovich and West (2000) have made a case for individual differences in reasoning ability (Gf) as a determinant of performance in reasoning tasks, such as syllogistic reasoning and other tasks stemming from research on logic and problem-solving.

In comparison, little research has been done on the relation between individual differences in cognitive capacities and the use of decision strategies. Two exceptions are Klayman's (1985) work with children and recent work by Bröder (2003) with younger adults. Klayman analyzed information search patterns of twelve-year-olds in different-sized matrices of information and found that these children already understood this sort of task fairly well and that they modified their strategies as a function of complexity. Additionally, Klayman investigated the role of working memory capacity. The results showed that an increase in number of alternatives led to increased use of simpler strategies mostly for those children with lower working memory capacity.

In a study evaluating the role of environmental structure, Bröder (2003) assessed the importance of individual differences in intelligence and working memory capacity in determining strategy use. He found that participants with higher intelligence were more likely to use a noncompensatory strategy, TTB, in an environment in which this strategy earned them the highest payoff. Working memory capacity, however, did not mediate strategy use, even under a condition of cognitive load, in which information was presented only briefly. Bröder admitted that this manipulation may not have been strong enough, because too little information needed to be stored to heavily tax participant's working memory capacities. Nevertheless, Bröder has proposed that while individual differences in intelligence are associated with adaptive strategy use, individual differences in working memory are not a triggering factor in strategy selection.

The two studies reported above provide different conclusions concerning the role of individual differences in cognitive capacity, in particular, regarding working memory capacity. However, these studies investigated distinct issues, assessed different populations, and used different experimental paradigms and measures. Thus, overall, the disparity between findings and the scarcity of studies investigating the issue of the role of cognitive capacity in determining strategy selection and, in particular, individual differences in cognitive capacities, makes it hard to draw strong conclusions. One goal of the present dissertation is to provide a clearer picture of these issues.

Strategy Application

The assumption underlying the adaptive toolbox approach to decision making (Gigerenzer et al., 1999) as well as of other approaches in this domain (Payne et al., 1993) is that when faced with the problem of making an inference based on a set of cues a decision maker completes a series of steps to arrive at a decision. This idea has its roots in more classic approaches such as Newell and Simon's (1972) Human Problem Solver and Card, Moran, and Newell's (1983) GOMS (goals, operators, methods, selection rules) model. In this view, strategy application refers to the process of carrying out a series of steps in an organized fashion to achieve a desired goal. In what follows, I present a particular formulation of these basic components of decision strategies and emphasize its contribution to our understanding of strategy application processes.

Elementary Information Processes

A particular taxonomy for the processes involved in multi-alternative decisions has been proposed by Payne et al. (1993). Payne et al. dubbed these basic components elementary information processes (EIPs), and included such units as reading an alternative's value on an attribute into short-term memory and comparing or adding the values of two alternatives, among others (see Table 1.2). The main idea behind this taxonomy is that simple components can combine in different ways to originate a particular strategy. In fact, this idea is taken up by the adaptive toolbox approach under the concept of building blocks (Gigerenzer et al., 1999), which represent basic units of strategies.

Table 1.2: Elementary Information Processes Postulated by Payne et al. (1993) as Basic Units of Strategies

EIP	Description
READ	Read an alternative's value on an attribute into short-term memory
COMPARE	Compare two alternatives on an attribute
DIFFERENCE	Calculate the size of the difference of two alternatives for an attribute
ADD	Add the values of an attribute in short-term memory
PRODUCT	Weight one value by another (multiply)
ELIMINATE	Remove an alternative or attribute from consideration
MOVE	Go to next element of external environment
CHOOSE	Announce preferred alternative and stop process

One methodological advantage of such formulation is the possibility to define strategies at a fairly detailed and computationally defined way. Moreover, a useful aspect of outlining the basic components of decision strategies is that it provides an estimate of their cognitive costs. For example, Johnson and Payne (1985) used EIPs as a measure of cognitive effort involved in applying a strategy. In particular, they counted the number of EIPs necessary to arrive at a decision while simultaneously measuring its accuracy relative to a normative model in different environments. Johnson and Payne concluded that different strategies differ both in terms of effort and accuracy but that this varies as a function of the environment (e.g., complexity of the task, presence of dominated alternatives). Using a similar framework, Payne, Bettman, and Johnson (1988) showed that in some conditions (i.e., time pressure) some heuristics which are less effortful can be more accurate than a truncated normative procedure. In addition, they pointed out that no single strategy did well across all conditions, suggesting once again that one must consider the fit between strategy and decision environment to understand strategy use. The same principle has been adopted by Gigerenzer, Czerlinski, and Martignon (1999) who counted EIPs to compare the speed and frugality of different decision strategies. Namely, they showed that, in the environment considered, TTB required on average less EIPs than multiple regression to arrive at a decision, leading them to conclude that TTB is a less cognitively effortful strategy.

An associated line of study has linked the estimated effort of strategies to behavioral data and subjective perceptions of effort. Bettman, Johnson, and Payne (1990) conducted an experiment in which 7 participants were trained to use strategies differing in the number of computations required to arrive at a decision. Additionally, after using each strategy participants were asked about perceived effort in using the rule. The estimates of effort based on the simulation work were then related to both decision time and the subjective perceptions. Compatible with the simulation results, EIPs were good predictors of time needed to reach a decision, and simple strategies such as lexicographic strategy (LEX; a general version of TTB; Fishburn, 1974), which involve fewer EIPs, were considered less effortful than a weighted additive rule (WADD; a general version of Franklin's rule). However, Bettman et al. reported that there were considerable individual differences in both use of the strategies (e.g., number of errors) and perception of effort. Whether these estimations were associated with participants' actual cognitive capacities was not investigated in this work, but Bettman et al. showed that incorporating the 7 participants' individual estimates of the required effort to execute decision strategies improved the explanatory power of their EIP-based model.

Another finding consistent with these results was obtained in a survey study concerning perceptions of decision strategies (Chu & Spires, 2003), which showed that, by and large, participants' perceptions of the accuracy and effort of various decision strategies agreed with researchers' deductions. For example, WADD was seen as one of the most cognitively demanding decision rules, while LEX was perceived as a simple and undemanding strategy. However, Chu and Spires also reported large individual differences in subjective perceptions; this finding provides additional support for the idea that individual characteristics may be an important factor in strategy application.

Summing up, decomposing strategies in more basic components has allowed researchers to implement strategies as computational models, simulate their performance in different situations, and thus estimate effort and accuracy of different decision rules as a function of environment characteristics. The results from this research suggest that the application of different strategies requires different amounts of computation and, therefore, cognitive effort. A second line of research strengthens this conclusion by relying on experimental work with trained participants and individuals' subjective perceptions of effort.

Cognitive Aging and the Use of Decision Strategies

Gigerenzer (2003) has argued that the study of bounded rationality could be extended into a lifespan perspective. The above discussion of the adaptive toolbox approach supplies us with two issues worthy of attention when considering cognitive aging. First, do older and younger adults differ in terms of *strategy selection*? One possibility is that cognitive aging affects the available repertoire of strategies. For example, the decrease in cognitive resources may make some tools too cumbersome to use, thus providing younger and older adults with a different set of strategies to choose from when making a decision. In accordance with this view, Sanfey and Hastie (1999) have predicted that older people are more likely to "exhibit choice strategies that have reduced 'cognitive load' requirements". Similarly, Gigerenzer (2003) hypothesized that because noncompensatory forms of decision making pose fewer cognitive demands they might be particularly fit to guide decisions at that point of the life span when cognitive capacities, such as recall memory, show severe decline. Additionally, cognitive aging may be associated with differences in adaptivity. Even assuming that younger and older adults have available a similar repertoire of strategies, the ability of choosing the right tool for the job may differ between age-groups.

Second, there is the issue of *strategy application:* Are there important age differences in the use of particular strategies? One could imagine that cognitive decline would not only influence which strategies are available or selected from the set but also how a particular strategy is employed.

As the following overview of the psychological literature on aging and decision making attests, empirical evidence concerning these issues is not conclusive. To obtain a good overview of the decision making and aging literature I conducted an extensive literature search using systematic literature review methods (e.g., Deville, Buntinx, Bouter, Montori, de Vet, van der Wint, & Bezemer, 2002). The procedure and results of this search are presented in Appendix A.

In what follows, a review of the papers identified in the literature search is given by discussing the main issues covered in the experimental papers and, afterwards, discussing some potential limitations of previous work and avenues for further study. The topics under analysis concern age differences in central aspects of decision making, such as (1) the comprehension of information and consistency of information integration, (2) learning the relation between cues and a criterion, and, more central to the present purposes, (3) use of decision strategies. Additionally, for comparison purposes, I give a brief overview of research on age differences in everyday problem solving and strategy use in domains other than decision making.

Comprehension of Information and Consistency in Information Integration

Hibbard, Slovic, Peters, Finucane, and Tusler (2001) investigated a fundamental skill in decision making: correctly interpreting comparative data. They contrasted the performance of older and middle-aged adults in a questionnaire study involving understanding information concerning health-plan options. Older participants made almost three times as many comprehension errors as the younger participants (25% vs. 9%). Moreover, education did not explain all the variance in comprehension of the older group, suggesting that the effect is not due to literacy alone but also an aging effect.

Finucane, Slovic, Hibbard, Peters, Mertz, and Macgregor (2002) compared two age-groups in a task involving literal and inferential comprehension questions about drug labels. Older adults displayed significantly more error than younger adults on all comprehension questions (32% vs. 14 %). Additionally, Finucane et al. used an evaluability task (Hsee, 1996) to assess consistency of information integration. In the evaluability task participants are asked to evaluate options first independently and later on, after completing some filler tasks, in conjunction. Results indicate that both younger and older adults tend to change their preferences when allowed to make joint evaluations but that older adults show stronger inconsistency across contexts. As in Hibbard et al. (2001), increasing age was associated with more comprehension errors and inconsistent preferences even when covariates, such as education or income, were considered. Similarly, Finucane, Mertz, Slovic, and Schmitt (2005) assessed age differences in comprehension ability and preference consistency in the domains of health, finance, and nutrition. To investigate the role of task demands, the authors varied number of options and respective attributes (e.g., 1x4, 3x4, 4x6, 9x4 information boards). Older adults made more errors than younger adults regardless of task domain or complexity of the task. Additional correlational analyses showed that a large amount of age-related variance in performance on the decision tasks could be accounted for by variables such as speed, knowledge, health measures, and education.

Overall, the findings on age differences in consistency of choices are inconclusive. While the papers described above found that older adults were less consistent in the choices they made (Finucane et al., 2002, 2005; Hibbard et al., 2002), other studies suggest that older adults can be more (Kim & Hasher, 2005; Tentori, Osherson, Hasher, & May, 2001) or as consistent as younger adults in choice situations (Capon, Kuhn, & Gurucharri, 1990). For example, Kim and Hasher (2005) have found that regardless of expertise, older adults were less subject to attraction effects, which can be defined as the effect of increasing the proportion of people choosing an alternative from an initial choice set by adding an irrelevant alternative to the set.

Summing up, these studies suggest that there are important differences between younger and older adults in comprehension of information in choice tasks and that these relate to factors such as cognitive ability, and education. However, the picture is not so clear concerning age differences in consistency of choices. One limitation of the work reported here is that it has focused mostly on "demonstrating age differences in comprehension and consistency tasks, rather than examining specific mechanisms underlying the differences" (Finucane et al., 2002, p. 159). Consequently, this research has not directly informed researchers on age differences at the level of the decision mechanisms employed.

Learning cue-criterion relations

To decide between options based on a set of cues it is necessary to understand the relation between the cues and the criterion of interest. Some work using multiple-cue probability learning (MCPL) tasks has investigated the issue of whether there are age differences in this ability. MCPL tasks involve making inferences about some criterion that cannot be directly known. The judgment is usually based on several cues that are imperfectly related to the criterion and correlated to one another. This view of judgment is related to Brunswik's (1952) Lens Model and Hammond's Social Judgment Theory (Hammond & Stewart, 2001). Within this framework, one needs to infer the value of different objects on a criterion to, later on, decide between alternatives. MCPL tasks can be manipulated in several respects, such as in terms on the number of cues available, the intercorrelations among cues, or the form of the relation between cues and criterion (e.g., positive, negative). Performance in MCPL tasks is measured by the correlation between judgments and criterion values. Chasseigne and colleagues (Chasseigne, Grau, Mullet, & Cama, 1999; Chasseigne, Ligneau, Grau, Le Gall, Roque, & Mullet, 2004; Chasseigne, Mullet, & Stewart, 1997) have studied the ability of younger and elderly people to learn relations between cues and criterion. Overall, these studies suggest that younger and older adults are equally able to learn direct relations between cues and criterion across different levels of complexity (i.e., number of cues) and uncertainty (i.e., criterion predictability). However, when inverse relations are considered, that is, when the cue is negatively correlated with the criterion, differences between age-groups emerge, with the majority of older adults having problems with all but simple one-cue tasks, while younger adults are able to learn cue-criterion inverse relations even in multiple-cue settings. Chasseigne et al. (2004) have taken the fact that older adults' difficulty in dealing with non-default cases (i.e., inverse cue-criterion relation) in more cognitively demanding situations as a typical effect of aging deficits in executive functions.

Some work on judgments of conditional probability supports this view. Spaniol and Bayen (2005) had participants learn conditional probabilities from exposure to a set of instances, namely, patients having different diseases, and asked them to judge the probability of undiagnosed patients having the different diseases on the basis of their symptoms. The authors interpreted their data using an exemplar-based approach to inference and suggested that some of the difficulties encountered by older compared to younger participants in giving accurate estimates of frequency were a function of memory deficits, modelled as lower value in an encoding parameter of their model.

Information Search and Use of Decision Strategies

Some research has used process tracing techniques to investigate age differences in preferential choice (Johnson 1990, 1993; Johnson & Drungle, 2000; Riggle & Johnson, 1996; Stephens & Johnson, 2000). Overall, this line of research suggests that retirement-age participants use less information and spend more time viewing pieces of information than younger adults in choice scenarios. Table 1.3 summarizes the main findings in this set of studies, and associated effect sizes (Cohen, 1988). As can be seen in Table 1.3, concerning the proportion of information searched, overall, older adults look up a smaller proportion of the information available compared to younger adults. However, the size of the effects ranges from negligible to very large effects (.05 to 1.29). In what concerns time spent per decision, older adults took longer to arrive at a decision than younger adults. However, the range of effect sizes is also very large (negligible to huge effects; .07 to 1.49).

These studies also suggest some factors that moderate age differences in decision making. First, expertise may play a role. For example, two papers investigated decision making in purchase of over-the-counter medications (Johnson & Drungle, 2000; Stephens & Johnson, 2000). In these studies, which concerned a domain in which older adults have higher expertise than younger adults, older participants showed a more organized information search than their younger counterparts; for instance, older adults consistently looked for potential side-effects when choosing medications. Moreover, Johnson and Drungle (2000) reported no significant difference between younger and older adults in terms of amount of information searched in this domain (see Stephens and Johnson, 2000, however, who found the effect).

Second, some age differences in strategy use may be due to differences in strategy selection processes. Johnson (1993) considered the impact of think-aloud and self-report instructions on the decision making performance of younger and older adults. Think-aloud techniques increased the total time for younger and older adults but did not magnify differences between groups. The use of self-report techniques produced a weak interaction such that older adults that reported how they would make a decision before performing the task made their decisions as quickly as younger adults. These results suggest that at least part of the age differences in decision making performance boil down to strategy selection and preparation.

Table 1.3: Summary of Results Concerning Age Differences in Proportion of Information Searched and Time Per Decision in Studies Using Information Boards

Paper	Domain	Information Board	Proportion of Information Searched	Time Per Decision
Johnson (1990)	Purchasing a car	6x6	*d* = 1.29	*d* = 1.49
Johnson (1993)	Renting an apartment	5x12	Exp. 1 (silent condition) *d* = .67 Exp. 1 (think-aloud condition) *d* = .74 Exp. 2 (self-report before cond.) *d* = .82 Exp. 2 (self-report after cond.) *d* = .52	*d* = .22 *d* = .07 *d* = .15 *d* = .65
Johnson & Drungle (2000)	Purchasing over-the-counter medications	7x7	Medication 1 *d* = .23 Medication 2 *d* = .14 Medication 3 *d* = .36 Medication 4 *d* = .05	—[1]
Riggle & Johnson (1996)	Voting on political candidates	8x6	Condition 1 *d* = .58 Condition 2 *d* = .58	*d* = .94 *d* = .84
Stephens & Johnson (2000)	Purchasing over-the-counter medications	7x7	*d* = .72	*d* = .23

Concerning differences in terms of the strategies used, the results provided by this literature are scarce and inconclusive. Johnson (1990) distinguished between compensatory and noncompensatory decision rules based on variability in amount of information searched across alternatives. Her results indicated that a higher proportion of younger adults could be classified as using a compensatory strategy (80%) compared to older adults (25%). Furthermore, Johnson reported that the best single predictor of use of compensatory strategies was age and that intelligence (vocabulary measure) did not significantly improve prediction when added to age in a regression model. However, later studies using similar measures found no significant differences in strategy use (Johnson, 1993; Riggle & Johnson, 1996), while

[1] Johnson & Drungle (2000) failed to report the total time per decision and thus effect sizes for this variable are not reported here.

other did not investigate the issue at all (Johnson & Drungle, 2000; Stephens & Johnson, 2000).

More recently, Chen and Sun (2003) tested younger and older adults in a simulated yard sale task. In this task, participants could use two optimal strategies that differed in their cognitive demands to successfully sell a series of objects at the highest price possible. Although younger and older adults did not differ in monetary earnings, older adults were more likely to use the simpler strategy, which involved fewer memory requirements. The authors speculated that this may be due to reduced working memory capacity of older participants.

In sum, research on the impact of aging on decision making behavior suggests that older adults seem to differ from younger adults in their information search; older adults look up less information and take longer to make a decision than younger adults. Nevertheless, the studies conducted in this domain shows clear limitations. First, they deal mostly with individual preferences and not objective cue-criterion relations. Second, they relied only on very large information boards, begging the question of whether older adults' decision making limitations are observable also in tasks imposing fewer cognitive demands. More crucially, it is not clear from these results to what extent older and younger adults actually differ in the strategies employed or the underlying causes for potential differences in this respect. One solution to the first problem would be to use a comparative model fitting approach, which would allow discerning more precisely the strategies in use. Additionally, a more precise consideration of the cognitive aspects underlying strategy use should be studied to provide an understanding of the basis for potential age differences in strategy use.

Everyday-problem solving

Some work has studied age-related changes in decision making in natural settings. For example, Zwahr, Park, and Shifen (1999) have found age differences in deciding about estrogen replacement treatment. In their study increased age was related to perceiving fewer treatment options and a lower quality rational for the final choices. Streufert, Pogash, Piasecki, and Post (1990) tested participants in a group context in a simulated management situation and observed that older teams (65- to 75-year-olds) made fewer decisions and requested less information compared to younger (28- to 35-year-olds) and middle-aged teams (45- to 55-year-olds). These papers suggest that younger and older populations differ in their performance in the context of naturalistic complex decision tasks. A meta-analysis of 28 studies on everyday problem-solving (Thornton & Dumke, 2005) also supports the idea that these skills are not preserved in late adulthood. In particular, the meta-analysis suggests that older adults have some disadvantage compared to younger adults in finding different and accurate solutions to problems, and providing good rationales for these solutions.

Strategy Use in other Domains

How does the literature on strategy use in domains other than decision making bare on our questions of interest? Do results suggest that younger and older adults use different strategies? Do they use strategies differently? Are older adults generally less adaptive?

There is some evidence that younger and older adults may differ in the strategies that they use, specifically, older adults may tend to use less cognitively demanding strategies when learning paired associates (Dunlosky & Hertzog, 1998, 2000), and in arithmetic tasks (Geary, Frensch & Wiley, 1993). However, age-related differences in strategy use are not always observed (cf. Salthouse, 1991). Cohen and Faulkner (1983), for example, found no age differences in strategy use in mental rotation and linguistic verification tasks.

Another aspect of strategy use concerns application. In this regard, younger people seem to be faster and more accurate than older adults with most strategies, and these differences tend to be larger with the most resource-demanding strategies or when these are used on more difficult problems (Dunloski & Hertzog, 2001; Geary et al., 1993; Lemaire, Arnaud, & Lecacheur, 2005). However, some studies have reported more accurate use of strategies in older compared to younger adults in simple addition tasks (e.g., Geary & Wiley, 1991).

Concerning adaptivity in strategy use, little work has been done investigating age differences. One exception is Lemaire et al.'s (2005) work on age-related changes in the ability to choose the most precise strategy when solving computational estimation problems (2-by-2-digit multiplication problems). Overall, when solving these tasks older adults were less accurate and showed less adaptivity in strategy use, choosing estimation strategies less appropriate for each problem. However, both age-groups were flexible enough to adapt their strategy use to increases in accuracy demands.

In sum, research on aging and strategy use in domains other than decision making suggests that younger and older adults may use different strategies when solving a particular problem. Although research on adaptivity in strategy use is scarce, the existing evidence suggests that older adults may have difficulties in choosing strategies in an adaptive fashion. Moreover, older adults seem to have more difficulties in applying strategies effectively, making more errors and being slower than younger adults.

Reviews of the Decision Making and Aging Literature

All three reviews on decision making and aging are unanimous in stating that too little is known about the relation between the two (Peters et al., 2002, in prep; Sanfey & Hastie, 1999; Yates & Patalano, 1999). Nevertheless, they agree that from the data gathered so far, older adults seem to use less information and take longer to view it when making a decision, have problems with more complex relations between criterion and cues, have greater difficulties in understanding information concerning available options, and may show less consistency in their decisions. Suggestively, all three reviews assume that increased reliance on simpler, less effortful decision strategies may take place with increased age because of decline in basic cognitive capacities. These different conclusions map relatively well to other research in everyday-problem solving and strategy use in domains other than decision making.

Although these conclusions seem warranted, there are some shortcomings in the work conducted so far that may limit our understanding of the relation between decision making and aging. First, most research conducted so far has focused little on mechanisms. Consequently, we know little about which strategies older adults use and how this compares to younger adults' behavior. Second, although some efforts have been made to understand the relation between cognitive aging and strategy use it is not clear which cognitive components underlie decreases in performance, for instance, to what extent deficits in basic components, such as working memory, speed, and inhibition-related functions, can account for age differences in strategy selection and application. Finally, there has been little focus on adaptivity in behaviour. Although adaptive strategy use seems to be a central component of effective decision making (cf., Gigerenzer et al., 1999) and adaptive selection is a central concept in aging research (e.g., Baltes & Baltes, 1990) no systematic study of age-related changes in how individuals adapt their use of decision strategies to different environments has been attempted.

Summary and Outlook

Research on cognitive aging has pointed out that there are both patterns of decline and compensation associated with increased age. This has produced a vision of successful aging as the adequate orchestration of the demands posed by the environment with the age-related gains and losses in intellectual abilities. In this introduction I argued that decision making is an appropriate area for studying these developmental dynamics as adaptive decision making is the result of the regulation between cognitive resources and task demands. Hence, studying age-related changes in decision making abilities provides an ideal test bed for theories of successful aging.

In this work, the adaptive toolbox approach provides a framework to understand the relation between cognitive aging and decision making. The adaptive toolbox approach sees decision making as the result of the adaptive deployment of specific strategies. In this introduction, I expanded the toolbox metaphor to include a crucial distinction concerning two aspects of strategy use, 1) strategy selection, which concerns how adaptive one is in choosing a strategy as a function of one's own resources and the characteristics of the decision problem, and 2) strategy application, which concerns how effectively one can use a particular strategy once it has been selected.

In reviewing the work stemming from the adaptive toolbox and related visions of decision making it was concluded that while considerable progress has been made in understanding the fit between inference mechanism and environments, little knowledge has been gained concerning the relation between strategy use and individual characteristics. Furthermore, while several researchers have predicted that older people are more likely to experience losses in the decision making domain due to reduced cognitive resources, no firm understanding exists of how cognitive resources in either younger or older populations relate to selection and application components of strategy use.

Summing up, we know little about how cognitive aging is associated with the different facets of the use of decision strategies, namely, strategy selection and strategy application, and how cognitive decline and compensation processes determine the use of decision mechanisms. In an effort to contribute to bridging this knowledge gap, this dissertation focuses on two general questions.

First, Chapter 2 contributes to an answer to the question of how age-related changes in basic cognitive components relate to strategy selection, and how this is reflected in changes in adaptive use of strategies. This is accomplished by investigating strategy selection behavior of younger and older adults in the context of simple decision making tasks and relating strategy use to measures of both mechanics and pragmatics of cognition.

Chapter 3 focuses on a second set of questions, namely, how basic cognitive components relate to strategy application, and how this is reflected in the efficiency with which different strategies are employed by younger and older adults. The approach adopted involves deriving predictions from a computational model of strategy application and testing the resulting predictions empirically.

The theoretical aim of this dissertation is to contribute to the understanding of the relation between ontogeny and higher-order cognition. Although inherently limited in its scope, the adopted approach provides some insights in this regard by researching the effects of cognitive aging on decision making abilities. Hopefully, understanding the relation between basic cognitive processes and decision making will additionally show its applied potential by improving both younger and older adults' quality of life.