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The Aging Decision Maker: Cognitive Aging and the Adaptive Selection of Decision Strategies

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Are older adults' decision abilities fundamentally compromised by age-related cognitive decline? Or can they adaptively select decision strategies? One study ($N = 163$) investigated the impact of cognitive aging on the ability to select decision strategies as a function of environment structure. Participants made decisions in either an environment that favored the use of information-intensive strategies or one favoring the use of simple, information-frugal strategies. Older adults tended to (a) look up less information and take longer to process it and (b) use simpler, less cognitively demanding strategies. In accordance with the idea that age-related cognitive decline leads to reliance on simpler strategies, measures of fluid intelligence explained age-related differences in information search and strategy selection. Nevertheless, both young and older adults seem to be equally adapted decision makers in that they adjust their information search and strategy selection as a function of environment structure, suggesting that the aging decision maker is an adaptive one.

Keywords: aging, decision making, strategy, adaptive

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A common concern of both research on decision making and research on aging is how individuals balance their personal resources and the demands of a task to behave adaptively. Researchers in decision making have argued that people are equipped with a repertoire of strategies to solve the decision problems they face, and they select strategies as a function of both cognitive constraints and characteristics of the decision situation (e.g., Gigerenzer, Todd, & the ABC Research Group, 1999; Payne, 1976; Payne, Bettman, & Johnson, 1988, 1993; Simon, 1956; Svenson, 1979). Research on aging has examined loss of cognitive capacity with age and has investigated how individuals compensate for these losses, for example, by relying on knowledge originating from years of experience (e.g., Baltes & Baltes, 1990; Baltes, Staudinger, & Lindenberger, 1999). The goal of the present article was to bring these two areas together. More specifically, we examined how the strategies people select depend on the nature of the information available in the environment[1] and on the individual's cognitive resources, which change across the life span.

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In the remainder of this introduction, we first summarize the strategy approach to decision making, which sees decision behavior as the result of the selection of specific strategies. Second, we provide an overview of previous work on cognitive aging and strategy selection. Finally, we hypothesize how age-related cognitive change may impact adaptive strategy selection and describe the experimental study.

The Strategy Approach to Decision Making

The assumption that there are multiple strategies to solve the problems we face is common to various research domains, including preferential choice (Einhorn, 1970; Payne et al., 1988), mathematical skills (Lemaire & Siegler, 1995), and memory (Coyle, Read, Gaultney, & Bjorklund, 1998). The strategy approach assumes that people select a strategy that is successful in a specific situation—that is, they adapt their strategy use to the structure of the task (Gigerenzer & Selten, 2001; Gigerenzer et al., 1999; Rieskamp & Otto, 2006; Simon, 1956). For example, in the inference domain, in which people can make use of several cues to infer objects' criterion values, an environment can be statistically characterized by low or high correlations between cues. When cues are only moderately correlated with each other, high inference accuracy often results from integrating all available information, whereas with strong correlations between cues a heuristic that focuses on a single cue is often sufficient for making accurate inferences (cf. Dieckmann & Rieskamp, in press). Moreover, in many cases, such simple strategies can outperform strategies that

[1] We use environment to refer to the objects or conditions by which one is surrounded, more specifically, the statistical structure of the relevant set of objects or conditions.

integrate information, particularly when it comes to making predictions (Gigerenzer et al., 1999). Accordingly, it is assumed that cognition and environment are deeply intertwined: Having a repertoire of strategies allows people to choose those that fit specific environments and therefore perform adaptively.

When assuming that people have a repertoire of strategies for solving different problems, the pressing question of how people select strategies from their repertoire arises. Cost–benefit approaches to strategy selection propose that decision makers establish a balance between their personal resources and the expected benefits of selecting a particular strategy (Beach & Mitchell, 1978; Christensen-Szalanski, 1978; Payne, Bettman, & Johnson, 1993). According to these theories, each strategy can be evaluated on two dimensions, costs and benefits. The costs are related to the cognitive effort necessary to apply a strategy, whereas the benefits are related to the accuracy of the strategy. The decision maker anticipates, although not necessarily deliberately, the effort required to apply and the accuracy obtained from applying the strategies, selecting the most appropriate for the problem at hand. Empirical evidence for these cost–benefit models lies in people's apparent skill at selecting strategies appropriate for the task. For example, people rely on simpler decision strategies when the task involves choosing from a large number of alternatives (e.g., Ford, Schmitt, Schechtman, Hults, & Doherty, 1989; Payne, 1976; Payne et al., 1993), when they are under time pressure (Payne, 1976; Payne et al., 1993; Rieskamp & Hoffrage, in press; see Svenson & Maule, 1993, for a review), or when there are high costs associated with searching for information (Bröder, 2000; Newell & Shanks, 2003).

Age-Related Changes in Strategy Selection

Research on aging and strategy selection suggests that young and older adults may select different cognitive strategies. For example, older adults tend to select less cognitively demanding strategies compared with young adults in the arithmetic computation and memory domains (Dunlosky & Hertzog, 1998, 2000; Geary, Frensch, & Wiley, 1993), and they may have difficulties selecting appropriate strategies for a particular problem than young adults (e.g., Lemaire, Arnaud, & Lecacheur, 2004). Overall, these findings suggest that age-related cognitive decline may lead to deficits in adaptive strategy selection. Yet age-related differences in strategy selection are not always observed (cf. Salthouse, 1991); researchers on aging have found sustained or improved strategy use in old age in some domains, such as spatial cognition and arithmetic division (e.g., Cohen & Faulkner, 1983; Geary & Wiley, 1991).

Research on decision making and aging (for reviews, see Mather, 2006; Peters, Finucane, MacGregor, & Slovic, 2000; Sanfey & Hastie, 1999) suggests that older adults use less information and view it longer when making a decision (Johnson, 1990, 1993; Johnson & Drungle, 2000; Riggle & Johnson, 1996), have problems with more complex relations between criterion and cues (e.g., Chasseigne et al., 2004), have greater difficulties in understanding information concerning available options (Finucane, Mertz, Slovic, & Schmidt, 2005; Finucane et al., 2002), show rapid forgetting of the options' values (Wood, Busemeyer, Koling, Cox, & Davis, 2005; but see Kovalchik, Camerer, Grether, Plott, & Allman, 2005), and are less consistent in their decisions (Finucane et al., 2002, 2005; but see Kim & Hasher, 2005). These findings correspond well with research in everyday problem solving, suggesting decline in performance associated with increased age (Thornton & Dumke, 2005).

Most of the previous work has focused on showing age differences in various preferential choice and comprehension tasks "rather than examining specific mechanisms underlying the differences" (Finucane et al., 2002, p. 159). Consequently, little is known about age-related differences in the selection of decision strategies. Moreover, the existing evidence is inconclusive; some work suggests that older adults tend to use less information-intensive strategies compared with young adults (Chen & Sun, 2003; Johnson, 1990), whereas other work does not (Johnson, 1993; Riggle & Johnson, 1996). More important, past research has neglected the question of to what extent the ability to choose appropriate strategies for a particular environment is age related. In the present work, we evaluate whether young or older adults differ in the adaptive selection of strategies for an inference problem and look for the potential underlying causes.

Intellectual Functioning and Adaptive Strategy Selection

Crystallized intelligence and fluid intelligence, two main components of intellectual functioning, undergo different change trajectories across the life-span (Horn & Cattell, 1967). How do these components relate to decision behavior? Fluid intelligence declines with age (Baltes et al., 1999), and age-related decline in its components (e.g., working memory, speed, inhibitory function) may impact adaptive strategy selection. In fact, decline in fluid abilities has been related to age-related differences in decision-making behavior (e.g., Finucane et al., 2005). Bröder (2003) also showed that individual differences in fluid abilities are associated with the adaptive selection of decision strategies (for an example in another domain, see Schunn & Reder, 2001).

We assume that deficits in fluid intelligence impact strategy selection by setting an upper limit on the cognitive effort that can be expended, constraining the range of possible strategies that can be used in a particular situation. For instance, information-intensive strategies are likely to be out of reach of individuals with severe memory limitations. Of course, selecting simpler strategies also affects basic levels of the decision process, such as the search for information: Simpler strategies tend to require less information than more complex ones (e.g., Rieskamp & Otto, 2006). This perspective is in line with evidence that suggests older adults look up less information before making a decision (Johnson, 1990, 1993) and the hypothesis that older adults may rely more on strategies that require fewer cognitive resources (Gigerenzer, 2003; Sanfey & Hastie, 1999). This view leads to the expectation that older adults select strategies less adaptively compared with young adults: Older adults might have to rely on simpler strategies, regardless of environment structure.

Crystallized intelligence usually increases over the life span and can be seen as a reflection of experience. Previous work on decision making suggests that crystallized intelligence may not be a major determinant of age differences in information search (Johnson, 1990). However, the relation between crystallized intelligence and adaptive strategy selection has not been investigated. Theories of successful aging suggest that increases in experience may compensate for age-related cognitive decline and lead to a "higher level of adaptive capacity" (Baltes et al., 1999, p. 478).

Crystallized intelligence or knowledge could be associated with a better understanding of the fit between the statistical structure of environments and particular cognitive strategies, leading to increased adaptivity in decision making. If knowledge is a good predictor of success in selecting the appropriate strategy for a task environment, one could expect older adults to outperform young adults in selecting adaptive strategies for a particular task or environment, at least to the extent that their strategy repertoire is not constrained by age-related cognitive decline.

Summing up, considering the role of both fluid and crystallized intelligence provides two possible views of the impact of aging on decision making. First, a "negative" view suggests that age-related cognitive decline constrains the repertoire of strategies potentially applicable in an inference situation. This could lead older adults to rely on simpler strategies regardless of environment structure. A second, more "positive" view suggests that older adults' experience may have equipped them with knowledge concerning the correspondence between strategies and environments, that is, knowledge about what is the right tool for a particular job. In this case, older adults may be as adaptive as young adults in their strategy selection, at least to the extent allowed by their cognitive abilities. Our study aimed to increase our understanding of how these two processes play out in determining adaptive strategy selection.

Overview and Logic of the Present Study

Our study investigated the impact of cognitive aging on the adaptive selection of strategies in an inference situation. The participants had to infer which of two diamonds was more expensive, on the basis of sequential acquisition of cues concerning, for example, the diamonds' size, cut, and clarity. Participants were explicitly instructed about one of two environmental structures: an equal validities environment (i.e., an environment in which all cues shared the same predictive power) or an unequal validities environment (i.e., an environment in which all cues differed in predictive power and were ordered in descending order as a function of predictive power). Participants were then asked to make a number of decisions in one of these environments and were given feedback about their performance only at the end of the inference task.

Participants' decisions were compared with the predictions of decision strategies to determine whether young and older adults selected appropriate strategies as a function of environmental structure. We chose three strategies to represent a wide spectrum of cognitive demands: Take The Best (TTB; Gigerenzer & Goldstein, 1996), Take Two (Dieckmann & Rieskamp, in press), and a weighted additive rule (WADD; e.g., Payne et al., 1988; see Payne et al., 1988, for additional strategies). TTB is the least effortful, followed by Take Two, and finally WADD.[2] This set allowed us to construct a reasonable number of discriminating trials in which the strategies led to different decisions, and thus we could meaningfully perform comparative model testing. TTB is a noncompensatory strategy, in which the decision is based solely on one piece of discriminating information. In our task, someone using TTB would first look up the information for the most predictive cue with which to compare the two diamonds (e.g., size of diamond) and select the diamond for which the cue speaks. If the first cue failed to discriminate between the diamonds (e.g., both diamonds are large), the second most predictive cue would be acquired, and so on, until a discriminating piece of evidence was found (e.g., one diamond was clear and the other cloudy). WADD is an information-intensive, fully compensatory strategy, in which the sum of all cue values (i.e., a large diamond would be coded as a 1 and a small one as a 0) is computed for each alternative and is multiplied by the cues' validities; the alternative with the largest sum is the one selected. In Take Two strategy, the alternatives are compared on successive cues and the information search is ended when two cues that favor one alternative are found; that alternative is selected. Thus, in Take Two, as in TTB, the alternatives are evaluated in a cue-wise fashion and the focus is on little information, but as in WADD, Take Two allows for compensation, so that two cues that favor one alternative can compensate for another cue that favors the other alternative.

Which strategies should people apply in the equal validities versus unequal validities environments? A cost–benefit analysis (Beach & Mitchell, 1978; Christensen-Szalanski, 1978; Payne et al., 1993) allows us to make specific predictions given some assumptions concerning participants' perceived accuracy and costs of decision strategies. Concerning perceived accuracy, in the equal validities environment, the different cues have the same validity, so that evidence provided by a single cue can be compensated for (overruled) by the evidence from other cues. Consequently, in the equal validities environment, individuals reasonably expect information-intensive strategies to have a higher expected accuracy than a noncompensatory strategy that relies on less information. In contrast, in the unequal validities environment, the cues have varying validities and thus the evidence of a high validity cue is less frequently overruled by the sum of the evidence of lower validity cues. As a consequence, participants may expect that in the unequal validities environment, an information-intensive strategy, such as WADD, does not have much of an advantage over a less information-intensive strategy. In this case, search costs may become a crucial factor in determining which strategy people select. Because TTB and Take Two require much less information than WADD to arrive at a decision, they should be selected more frequently in the unequal validities environment compared with the equal validities environment. In sum, people are more likely to select the cognitively demanding WADD strategy when faced with the equal validities environment, whereas the simpler strategies, TTB and Take Two, are more likely to be selected when people are confronted with an unequal validities environment.

How does cognitive aging play out in our task? The idea that decision-making behavior may be determined by both age-related cognitive decline and an increase in knowledge generates two sets of predictions.

1. The assumption that older adults' cognitive deficits constrain their repertoire of employable inference strategies suggests the following: (a) Older adults may be unable to select the more cognitively demanding WADD strategy and have to rely on simpler strategies, such as TTB or Take Two, regardless of the environment, and (b) older

[2] To quantify the cognitive effort associated with the strategies TTB, Take Two, and WADD, we computed the number of elementary information processes (see Huber, 1980; Payne et al., 1988) each decision strategy required (see Supplemental Information for details).

adults should be constrained to search for less information and take longer to process acquired information compared with young adults. One further consequence of the assumption that cognitive capacity constrains the repertoire of employable strategies is that a significant proportion of age-related differences in strategy selection and information search behavior can be explained by individual differences in cognitive abilities (e.g., memory abilities).

2. An alternative view of cognitive aging that considers older adults' increase in knowledge leads to the following suggestions: (a) Older adults may better understand strategy–environment correspondence and thus be more adaptive than young adults, at least in those cases in which older adults are not constrained by capacity limitations. For example, older adults could be more apt to rely on simpler strategies such as TTB and Take Two in the appropriate unequal validities environment compared with young adults. (b) If this were the case, a measure of crystallized intelligence, such as verbal knowledge (Lindenberger, Mayr, & Kliegl, 1993), should account for a significant proportion of the age-related differences in strategy selection.

To test these predictions, we used two different environments and conducted a comprehensive assessment of intellectual abilities, which included measures of both fluid and crystallized intelligence. We thus aimed to contribute to the understanding of young and older adults' strategy selection as a function of both environment structure and individual characteristics.

Method

Participants

A total of 169 adults (83 young adults, 86 older adults) participated in the experiment. Most (85%) of the young adults were students at the Free University of Berlin and were on average 24 years old ($SD = 3.3$). The older adults were healthy members of the community with an average age of 71 ($SD = 4.9$). Most of the older adults were retired. Overall, the young adults took about 2.5 hr and older adults 3.5 hr to complete all tasks. Participants received a fixed hourly payment of 10 euros for taking part in the experiment. In addition, they received an extra bonus payment dependent on their performance. Specifically, they received an extra 10 euro cents for each correct choice. We had to exclude 6 participants from our final sample: One participant stuttered, making it difficult to test him in tasks demanding oral responses; 1 tried to tamper with the experimental program while performing the decision task; and 4 participants faced technical problems with the experimental program implementing the decision task. The final sample comprised 80 young participants (41 female, 39 male), and 83 older participants (49 female, 34 male).

Our study used a convenience sample, which probably led to a less heterogeneous and more educated sample than the elderly population at large. For example, our older sample had on average 2.4 more years of education than the sample from the Berlin Aging Study (Lindenberger et al., 1993). This of course may lead to overestimation of ability when trying to generalize our results to the population at large. In addition, despite the high level of educational achievement of our older sample (years of education, $M = 14$, $SD = 3.95$), our young sample had more years of education ($M = 16$, $SD = 2.55$). As a general strategy, we dealt with this issue by including years of education as a covariate in our analyses. Other generational and cohort differences may also be an issue when interpreting our results (Baltes, Reese, & Nesselroade, 1988). Consequently, caution should be used in interpreting group differences as differences due strictly to age, and we thus refer to differences between our young and older participants as age-related differences (as opposed to age differences).

Design

The study had two between-subject conditions varying the environments the participants encountered, in particular, the distribution of cue validities. The validity of a cue is defined as the conditional probability of making a correct inference with the cue on the condition that the cue discriminates. For example, a validity of 71% means that out of 100 paired comparisons in which a cue discriminates between two diamonds, the diamond with a positive cue value will be the most expensive in 71 of the cases. Participants in the condition with the equal validities environment were informed that all cues had a validity of 71%. In the second, unequal validities environment, the validities of the cues varied substantially. In this condition, the first presented cue had the highest validity, the second cue had the second highest validity, and so on. The validities presented were 81%, 71%, 69%, 66%, 63%, 60%, 57%, and 54%. The average discrimination rate, that is, the proportion of times a cue discriminated between the two objects, was 70% for all cues. We chose this medium-size discrimination rate, first, because it provided a large number of discriminating cues, which increased memory demands. Second, it prevented the possibility that after observing a cue value on one alternative, one could infer the cue value of the other alternative without acquiring this information: As the discrimination rate of a cue approaches unity, the incentive to look up the value for a second alternative decreases if one has seen the value on the first alternative.

All participants had access to the following cues: size, overall proportions of the diamond, crown proportions, pavilion proportions, size of table, color, clarity, and certification laboratory. All cues had binary values (e.g., big vs. small diamond, colored vs. uncolored diamond). The assignment of labels to cues was randomized across participants. Each participant observed a different set of 50 pair comparisons randomly generated with the constraints of having the previously specified cue validities and discrimination rate and an adequate number of discriminating trials for each pair of the three strategies (TTB, Take Two, WADD), in which each strategy in the pair would lead to different predictions in order to allow comparative model testing (at least 10 discriminating trials for each pair). The participants were paid 10 euro cents whenever they chose the more expensive diamond. However, note that no outcome feedback was given during the experiment, and payments were made after the experiment so they could not influence participants' inferences.

To examine the fit between the three inference strategies and the two task environments that we constructed, we examined the payoffs the participants could expect to receive, if they consistently used one of the inference strategies. WADD performed best in the equal validities environment with a mean expected payoff of 4.20 euros, followed by Take Two and TTB with a mean expected payoff of 3.90 euros and 3.60 euros, respectively. In contrast, in the unequal validities environment, TTB provided the highest expected payoff of 4.00 euros, followed by Take Two and WADD with an expected payoff of 3.90 euros and 3.60 euros, respectively. Thus, the participants would on average receive a higher payoff by applying WADD in the equal validities condition and TTB in the unequal validities condition.

We tested our young sample before testing our older sample. For the young adults, the experimenter used the first trial as a practice trial, and we consequently analyzed only the remaining 49 choices; thus the actual proportion of discriminating items varied slightly across participants. When we later tested older adults, we gave them 5 additional practice trials to make sure they understood the task and were familiarized with the computerized display and apparatus before performing the 50 experimental trials.

Measures

A battery of 11 psychometric tests was administered to all participants. The tests assessed various intellectual abilities including verbal knowledge (spot-a-word, vocabulary; Lindenberger et al., 1993), processing speed (boxes, digit symbol substitution, identical pictures; Lindenberger et al., 1993), reasoning (figural analogies, letter series, practical problems; Lindenberger et al., 1993), and memory (operation span, Hamm, 2002; Brown–Peterson test, Kane & Engle, 2000; forward digit span, Wechsler, 1981). A detailed description of each test can be found in the online Supplemental Information section.

Procedure

The participants first performed the inference task. On each trial, they had to infer which of two diamonds was more expensive. Participants were first familiarized with the task and the concept of cue validity. They were then informed about the structure of the environment in which they would make their inferences by receiving a listing of cues, their validities, and direction (i.e., which cue values were associated with more expensive diamonds). Participants performed 50 inferences on the basis of an information search with a computerized display. They were able to search up to eight cue values per diamond, and each cue value was briefly presented (2 s before disappearing) individually and only once. Participants had to touch appropriate buttons on a touch screen to obtain cue values and to make a decision (see Figure 1). Participants could make their decision at any point during each trial. The order of information acquisition was partially constrained, with participants having to follow a predetermined cue order, from the most valid to the least valid cue in the unequal validities environment. Participants were otherwise unconstrained in their information search, being able to search both values on one cue for the two diamonds before considering another cue (cue-wise search) or, alternatively, to search for all the cues on a single diamond before the second diamond was considered (alternative-wise search). Mixed strategies were possible as well in which participants could search, say, half the cues in an alternative-wise fashion and the remainder in a cue-wise search. Thus, participants were not overly constrained in terms of the strategies that they could employ. After participants performed the decision task, we assessed their cognitive capacity using the comprehensive battery of tests mentioned above.

Results

The Results section is structured as follows: First, we give an overview of participants' payoffs and information search in the inference task. Second, we report what proportions of their choices were predicted by the different strategies. How well participants conformed to the various strategies gives an indication of how well they were able to exploit the statistical structure of the conditions. We also classify participants as users of particular decision strategies on the basis of their decisions and information search. Third, we provide a description of participants' intellectual abilities. Finally, we assess the relation between individuals' information search and strategy use and their cognitive capacity.

Payoffs

How well did young and older adults perform in the two environments? To answer this question, we considered participants' monetary payoff in the inference task. A higher payoff resulted when participants made inferences in line with WADD in the equal validities condition and in line with TTB in the unequal validities condition. Consequently, participants' payoffs reflect their ability to select the appropriate strategy for an environment on the basis of their understanding of environment–strategy fit. In addition, to examine possible effects of practice, we considered participants' performance in the first half and second half of the sequence of inference trials. More specifically, we conducted a repeated measures analysis of variance with participants' payoff (first half vs. second half) as the dependent variable and with environment, age group, and their interaction as independent factors. The analysis revealed an effect of environment, which matches the strategies' differences in expected payoff between the environments (see Method section). Participants in the equal validities environment received a lower payoff ($M = 3.75$, $SD = .45$) than those in the unequal validities environment ($M = 3.95$, $SD = .4$), $F(1, 159) = 11.22$, $p = .001$, partial $\eta^2 = .07$. Older adults earned slightly less ($M = 3.7$, $SD = .5$) than young adults ($M = 4$, $SD = .35$), $F(1, 159) = 21.92$, $p < .001$, partial $\eta^2 = .12$. Although the difference between older and young adults' payoffs was slightly larger in the equal validities environment than in the unequal validities environment ($-.35$ vs. $-.20$), this interaction was not significant (partial $\eta^2 = .01$). The analysis did not detect significant changes in payoff across the two halves or an interaction with age (partial $\eta^2 < .025$), suggesting that young and older adults' performance was fairly constant across the series of trials.

Information Search

Participants' information search behavior was characterized by three measures (e.g., Bröder, 2003; Payne et al., 1993; Rieskamp & Hoffrage, 1999): *Number of acquisitions* (ACQ) concerns the depth of search and is defined as the total number of cue values looked up. *Search index* (INDEX; Payne, 1976) reflects the general pattern of information search. This variable aggregates two

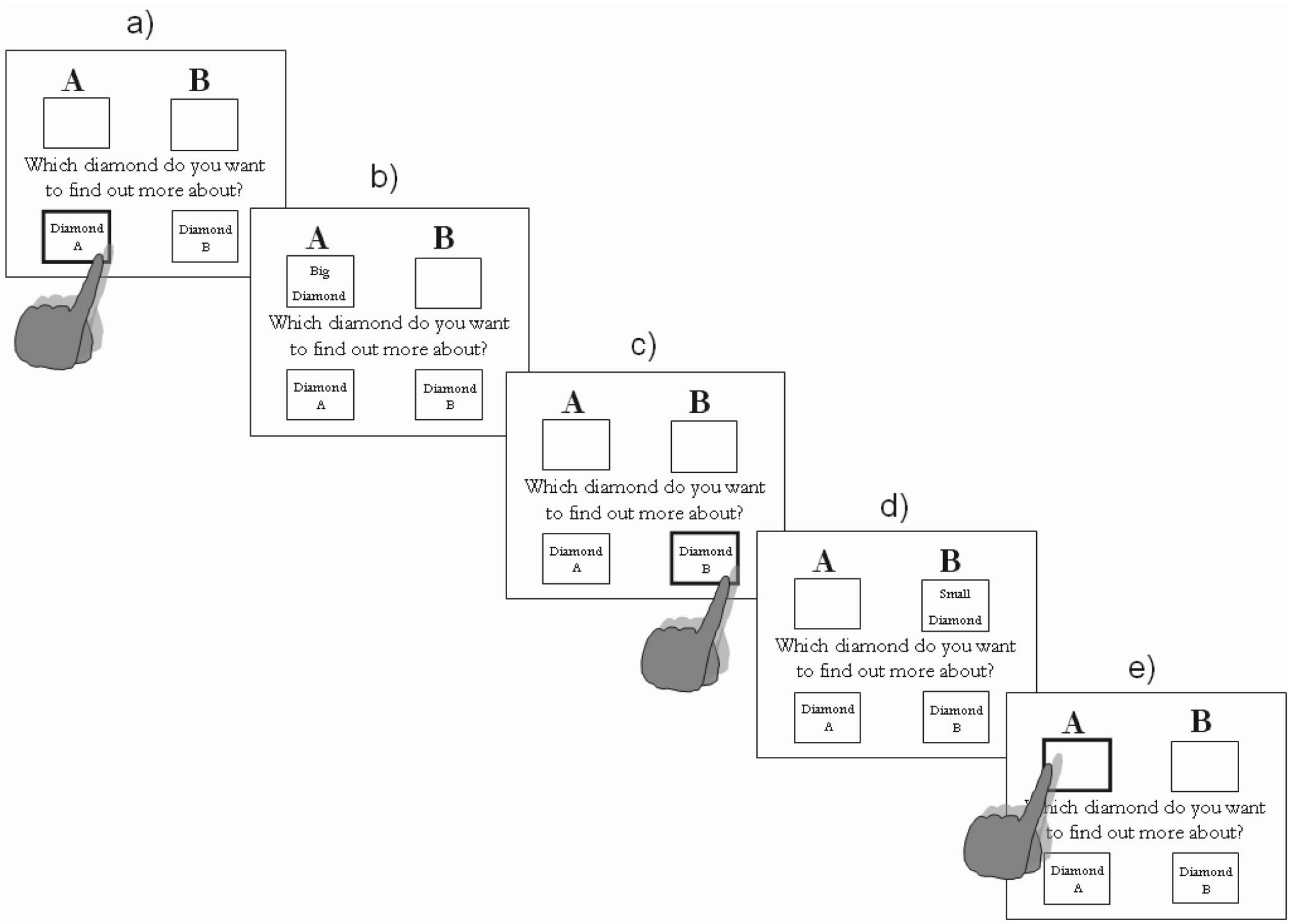

Figure 1. Experimental display and example of applying the Take The Best strategy: (a) The participant presses a button to see information concerning Diamond A and (b) observes the cue value for 2 s; (c) the participant presses a button to see information concerning Diamond B and (d) observes the cue value for 2 s; (e) the participant chooses Diamond A by pressing the appropriate button.

types of search transitions. Starting from the first cue on one of the diamonds, for example, size, another cue for the same diamond can be viewed, such as clarity (alternative-wise transition) or the size of the second diamond can be looked up (cue-wise transition). The index is determined by the number of alternative-wise transitions minus the number of cue-wise transitions, divided by the sum of these two types of transitions, yielding values from -1 to 1. Positive values indicate a more alternative-wise search, and negative values indicate a more cue-wise search. An alternative-wise search is inconsistent with TTB and Take Two, strategies in which a cue-wise search is expected. In contrast, for WADD, an alternative-wise search is more natural, but a cue-wise search that considers at least a majority of the cues is also possible. Finally, *look-up time* (TIME) refers to a person's median look-up time, that is, the median time each person took to process each cue value.

The values for the three search variables by age and environment are summarized in Table 1. The three measures are conceptually independent; for example, whether a participant searched for information in a cue-wise manner does not, in principle, determine the total number of cues for which he or she searched. Empirically, there is no relation between ACQ or TIME and INDEX ($r = -.10$, $r = .08$, respectively; ps $> .10$). However, the data suggest that those participants who could or were willing to search for more information also took less time to process it: There was negative correlation between amount of information searched for and time taken to process each cue value ($r = -.39$, $p = .04$).

We assessed whether there was an effect of environment structure as well as age on the search measures. We conducted a multivariate analysis of variance (MANOVA) with environment (equal validities vs. unequal validities) and age (young vs. older) as independent variables, and the three search measures described above as the dependent variables. Table 1 shows that both young and older participants searched for less information (ACQ), did so in a more cue-wise fashion (INDEX), and took longer to process each cue (TIME) in the unequal validities environment than in the equal validities environment, $F(3, 157) = 14.42$, $p < .01$, partial $\eta^2 = .22$. (Univariate tests showed that the effect held for all three variables.) Older adults searched for less information ($M = 9.62$, $SD = 4.52$) and took longer to process each cue value ($M = 1.48$, $SD = .60$) compared with young adults ($M = 12.07$, $SD = 3.10$;

Table 1
Means and Standard Deviations (SD) for the Search Variables by Age Group and Environment

Search variables	Young adults				Older adults			
	Equal validities		Unequal validities		Equal validities		Unequal validities	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Acquisitions	13.00	2.00	11.00	3.00	11.00	4.00	8.00	4.00
Search index	−.12	.74	−.61	.33	−.16	.75	−.40	.51
Look-up time	610.00	210.00	710.00	250.00	1,350.00	550.00	1,600.00	630.00

Note. Acquisitions represents the number of cue values searched for. Search index characterizes the type of information search: Positive values indicate a more alternative-wise search and negative values indicate a more cue-wise search. Look-up time represents the median time required to process a cue value (in milliseconds).

$M = .67$, $SD = .23$), $F(3, 157) = 44.85$, $p < .01$, partial $\eta^2 = .46$. Univariate tests showed that this effect held for ACQ and TIME but not for INDEX, in which the age groups did not differ substantially ($M = -.28$, $SD = .65$; $M = -.36$, $SD = .63$, older and young adults, respectively). Finally, there was no interaction between environment and age, $F(3, 157) = .84$, $p = .48$, partial $\eta^2 = .02$. For comparison, we computed the effect size of environment on the search variables for the two age groups independently. Both groups showed a small effect of environment (partial $\eta^2 = .20$, partial $\eta^2 = .26$, older and young adults, respectively), suggesting the two age groups were equally sensitive to the distribution of cue validities when searching for information.

One might wonder whether participants' inferences process changed during the experiment, considering the relatively large number of inferences. To examine potential changes, we compared participants' search behavior in the first half of the experiment with their search in the second half. More specifically, we conducted repeated measures ANOVAs with the different search measures as the dependent variables and the two halves of the experiment as a within-subject factor. Our results suggest that participants did not change how much information they considered over time (ACQ), $F(1, 160) = .02$, $p = .90$, partial $\eta^2 < .001$, the general pattern of information search (INDEX), $F(1, 160) = .001$, $p = .97$, partial $\eta^2 < .001$, or the time to process each cue (TIME), $F(1, 160) = 2.6$, $p = .11$, partial $\eta^2 = .02$.

Overall, the differences in participants' search behavior between the two environments are compatible with the adaptivity hypothesis (Gigerenzer et al., 1999; Payne et al., 1988), that is, the idea that people adjust their decision behavior according to the characteristics of the decision environment: Both older and young adults looked up less information in the unequal validities compared with the equal validities environment. Nevertheless, there were considerable age-related differences in search behavior, with older adults searching for less information overall and taking longer to do so compared with young adults.

Strategy Classification

To provide another measure of participants' performance, we determined the proportion of inferences that were correctly predicted by the three strategies we considered, TTB, Take Two, and WADD. As described earlier, if participants adapt to the environment they face, their choices should be more consistent with the WADD strategy in the equal validities environment and with the TTB and Take Two strategies in the unequal validities environment. In fact, WADD predicted 80% (*SEM* = .01%) of the inferences in the equal validities environment compared with TTB with 67% (*SEM* = .01%) and Take Two with 73% (*SEM* = .01%). In contrast, in the unequal validities environment, TTB was best, predicting 76% of the inferences (*SEM* = .01%) compared with Take Two with 73% (*SEM* = .01%) and WADD with 70% (*SEM* = .01%). These results suggest that the participants selected their inference strategies appropriately in the different environments.

To get a more detailed picture of participants' inference strategies, we classified participants as predominantly using specific strategies. A classification technique using participants' inferences and search behavior for classification is superior to a classification technique using only one type of information.[3] More specifically, we relied on a procedure that counts for each participant the number of inferences for which the information search *and* the final choice corresponded to the predicted search and choice by the particular strategy (see Supplemental Information). The strategy that predicted the most inferences correctly for a participant was assigned to the participant. Recall that TTB predicts that the information search stops after one discriminating cue has been encountered. In Take Two, the information search stops after seeing two discriminating cues favoring the same alternative. Finally, for WADD, we assumed that all cue values had to be searched on both alternatives. Participants were assigned to the strategy with the highest fit and those participants for which the fit of two or more strategies coincided were left unclassified.

The results of the classification are presented in Table 2. WADD was overall the preferred strategy, which replicates previous findings in the literature suggesting that compensatory strategies are preferred over noncompensatory strategies for unfamiliar tasks with low information search costs (e.g., Bröder, 2000; Rieskamp, 2006; Rieskamp & Otto, 2006). TTB was preferred by only a few

[3] To evaluate this classification method in comparison to a classification method based on participants' inferences alone, we performed a model recovery analysis. In a model recovery analysis, different models generate data; then whether a specific method identifies the data-generating model correctly is assessed. We examined classification methods that rely only on inferences, only on search behavior, or both. The analysis showed the superiority of the classification methods that consider search (for details, see the supplemental materials).

Table 2
Strategy Classification by Age Group and Environment

	Young adults				Older adults			
	Equal validities		Unequal validities		Equal validities		Unequal validities	
Strategy	No.	%	No.	%	No.	%	No.	%
TTB	1	2	1	3	3	8	14	33
Take Two	5	12	13	33	10	24	10	24
WADD	35	86	24	61	27	66	17	41
Unclassified	0	0	1	3	1	2	1	2
Total	41	100	39	100	41	100	42	100

Note. TTB = Take The Best; WADD = weighted additive rule.

participants. Due to the small number of participants assigned to TTB and to our desire to increase the reliability of our analysis, we grouped TTB users with the participants assigned to Take Two. The participants classified as using TTB or Take Two were then compared with those participants classified as using the information-intense WADD strategy. The rationale for this grouping is that WADD is an information-greedy strategy, which uses all available information, whereas TTB and Take Two stop the information search and therefore frequently only use a small proportion of the available information. Moreover, in contrast to WADD, both TTB and Take Two do not weigh cues according to their validities to arrive at a decision.

On the whole, the results concerning strategy selection behavior suggest that a large proportion of both young and older participants selected strategies as a function of environment structure. As can be observed in Table 2, a larger proportion of participants selected the simpler TTB or Take Two strategies in the unequal validities environment compared with the equal validities environment, whereas the opposite is true for the information-intensive WADD strategy, $\chi^2(1, N = 160) = 10.59$, $p < .01$, $w = .26$. Moreover, the effect of environment was evident in both the young, $\chi^2(1, N = 79) = 5.14$, $p = .02$, $w = .25$, and older sample, $\chi^2(1, N = 81) = 5.53$, $p = .02$, $w = .26$. Nonetheless, there was an age-related effect on strategy distributions. Older adults selected the simpler TTB or Take Two more often than did their young counterparts, $\chi^2(1, N = 160) = 7.23$, $p < .01$, $w = .21$. This result suggests that older adults may have a stronger initial preference for simpler, less cognitively demanding strategies than young adults.

Individual Difference Measures

Table 3 lists the 11 cognitive function tests in our battery. To construct composite measures from the individual tests, we hypothesized two ways of grouping tests into domains (see Wilson et al., 2002, for a similar procedure). In one grouping, we simply distinguished between measures of fluid and crystallized intelligence. In the second grouping, we looked at the functional domains of the different types of intelligence: the verbal knowledge component of crystallized intelligence and the components of reasoning, speed, and memory of fluid intelligence. We next developed an empirical grouping of the tests on the basis of the outcome of a principal components factor analysis (with varimax rotation) on the 11 tests. The analysis identified three factors and is summarized on the right side of Table 3. We grouped the tests that loaded higher than .50 on a common factor. As can be seen in Table 3, the empirical solution shows some resemblance to both theoretical groupings although it seems not to distinguish between the reasoning and speed subdomains. To quantify the agreement of each conceptual grouping with the empirical one, we used Kendall's tau, a measure that calculates the proportion of concordant pairs of tests (agreements between groupings) minus the discordant proportion (disagreements between groupings). When both young and older adults' scores were considered, the overall agreement between the factor analytic and the theoretical groupings was similar for both the two-factor and four-domain groupings: Agreement with the two-factor theoretical grouping was .42 ($p = .17$); agreement with the four-domain grouping was .37 ($p = .18$). However, when the factor analysis was performed separately for young and older adults, the four-domain grouping was better (.67 and .82, both $ps < .01$, young and older adults, respectively)

Table 3
Psychometric Information on the 11 Cognitive Tests

			Factor loading		
Test[a]	Grouping 1	Grouping 2	1	2	3
Spot-a-word	Crystallized	Verbal knowledge	−.23	**.86**	−.04
Vocabulary	Crystallized	Verbal knowledge	.37	**.69**	.10
Digit symbol	Fluid	Speed	**.82**	−.07	.10
Identical pictures	Fluid	Speed	**.82**	−.27	.06
Boxes	Fluid	Speed	**−.79**	.13	.03
Figural analogies	Fluid	Reasoning	**.83**	.08	−.05
Letter series	Fluid	Reasoning	**.78**	.12	.04
Practical problems	Fluid	Reasoning	**.64**	.25	−.03
Operation span	Fluid	Memory	**.69**	.21	.20
Brown-Peterson	Fluid	Memory	.21	−.04	**−.81**
Forward digit span	Fluid	Memory	.37	−.01	**.64**

Note. We distinguished between a general grouping of tests into those measuring fluid vs. crystallized intelligence (Grouping 1) and a more detailed one distinguishing between four functional domains (Grouping 2). Factor loadings are from principal components analysis with varimax rotation: Loadings of .50 or higher are in boldface.
[a] A detailed description of each test can be found in the Supplemental Information section.

compared with the two-factor grouping (.0 and −.14, both *p*s > .6, young and older adults, respectively). We chose the four-domain grouping because it fit better and allowed us to examine the impact of the different subdivisions of fluid intelligence on decision behavior.

Summary measures of the different domains were obtained by computing unit-weighted composites of the individual tests and scaling them (*T* metric, $M = 50$, $SD = 10$). Table 4 shows the average values for the different domains by age group. Average results seem to match earlier findings with similar populations (cf. Baltes & Lindenberger, 1997; Li et al., 2004). We also computed the correlations between the different factors. As can be seen in Table 5, the correlations among abilities are mostly positive, which replicates the positive manifold reported in the literature (e.g., Ackerman, Beier, & Boyle, 2002; Lindenberger et al., 1993). All variables correlate negatively with age with the exception of knowledge. These results reflect the known pattern of decline in fluid intelligence and sustained or increased knowledge with increasing age (Baltes et al., 1999). Also, as expected, participants in the two experimental conditions did not differ with respect to their abilities, $F(4, 158) = 1.39$, $p = .24$, partial $\eta^2 = .03$.

Cognitive Capacity and Information Search

Can the individual differences in cognitive capacity explain the observed age-related differences in number of cues looked up and look-up time? To answer this question, we performed an analysis consisting of the following steps: First, we estimated a set of regression models using the search variable as the dependent variable and age or each cognitive capacity measure as a predictor. Second, age and each capacity measure were used as predictors to test whether age substantially increased the fit (R^2) of the regression over each cognitive capacity variable. The first "restricted" regression including the cognitive capacity predictor was compared with the "complete" regression with both age and the particular cognitive capacity variable (cf. Cohen, Cohen, West, & Aiken, 2003, p. 465). This procedure allows one to test whether age adds to the explained variance when each individual difference measure has been considered, thus answering whether individual difference measures account for age-related variance in information search.

Table 6 summarizes the results of the regression analysis for the different cognitive measures. Age is negatively correlated with number of cue values acquired (ACQ) and positively correlated with the time participants took to look up a cue value (TIME), which reflects older participants' tendency to search for fewer cue values and to take longer to process information compared with young adults. Concerning the relation between individual difference measures and information search, the crystallized intelligence factor—verbal knowledge—was not associated with any of the information search variables. In contrast, the fluid intelligence factors—speed, reasoning, and memory—were related to both ACQ and TIME.

Do individual difference measures of fluid intelligence account for age-related variance in information search variables? As indicated in Step 2 of Table 6, when age was added as a predictor to the model with ACQ as a dependent variable, we detected a significant increment in explained variance beyond that provided by each cognitive capacity variable except when speed and reasoning were considered. Thus, speed and reasoning accounted for all the age-related variance in ACQ. Concerning the regression models with TIME as a dependent variable, age produced increments in explained variance beyond the effects of all individual difference factors. Speed and reasoning factors correlated strongly (see Table 5). To understand the contribution of speed and reasoning factors to the number of acquisitions, we considered a regression model using both as predictors. The results suggest that reasoning ($\beta = .34$, $p < .01$) but not speed ($\beta = .12$, $p = .20$) accounted for variance in ACQ. In sum, the results show that individual difference measures could account for considerable variance in search behavior: Individual differences in reasoning were able to explain all age-related variance in number of cues searched.[4] However, there were age-related differences in TIME not accounted for by individual difference measures.

To ensure our results were not influenced by differences in years of education between our young and older samples, we conducted the same set of analyses with education as a predictor of information search. The relation between education and information search was very small ($R^2 = .02$ for both ACQ and TIME), and the pattern of effects remained the same when education was included as a predictor in the regression models for the two age groups. Likewise, the pattern of results remains unchanged when environment was added as a predictor.

Table 4
Participants' Characteristics and Individual Difference Measures by Age Group

	Young adults		Older adults		Statistical test	
Measure	*M*	*SD*	*M*	*SD*	*F*	*p*
Knowledge	47.7	9.2	52.2	10.3	56.71	<.01
Speed	58.2	5.5	42.1	6.4	105.83	<.01
Reasoning	56.4	6.7	43.8	8.8	300.52	<.01
Memory	55.2	8.4	45.0	8.9	8.62	<.01

Table 5
Intercorrelations Among Abilities and Age

Measure	1	2	3	4	5
1 Knowledge	—	−.09	.06	.12	.23
2 Speed		—	.67	.55	−.82
3 Reasoning			—	.57	−.65
4 Memory				—	−.53
5 Age					—

Note. Significance levels: $r = .15$, $p < .05$.

[4] Lindenberger and Pötter (1998) have pointed out the limitations of hierarchical linear regression in providing an adequate account of variance explained due to the existing inter-correlations between predictor variables. Consequently, our findings concerning the role of fluid intelligence should receive further scrutiny in future studies which manipulate aspects of the decision task to specifically test the impact of different cognitive components (e.g., speed, reasoning, memory) on decision-making abilities.

Table 6
Hierarchical Linear Regressions with Search Measures as the Dependent Variables

	Acquisitions				Look-up time			
Variable	R^2	F	p	B	R^2	F	p	B
Step 1								
Age	0.12	21.61	<.01	−0.35	0.21	40.72	<.01	0.45
Knowledge	0.00	0.01	.92	0.01	0.00	0.57	.45	0.06
Speed	0.13	23.65	<.01	0.36	0.18	33.54	<.01	−0.42
Reasoning	0.20	39.30	<.01	0.45	0.13	24.12	<.01	−0.36
Memory	0.09	14.87	<.01	0.29	0.07	12.66	<.01	−0.27
Step 2								
Knowledge + age	0.13	23.28	<.01	0.10	0.20	40.36	<.01	−0.05
Speed + age	0.01	1.52	.22	0.23	0.04	7.40	<.01	−0.15
Reasoning + age	0.01	1.14	.32	0.38	0.08	16.20	<.01	−0.12
Memory + age	0.05	9.30	<.01	0.15	0.13	26.17	<.01	−0.05

Note. In Step 1, B corresponds to the age coefficient or to the cognitive abilities coefficients. In Step 2, R^2 represents the difference between R^2 of the model with age and each capacity as predictors and that of a model with only the cognitive capacity measure as a predictor.

Cognitive Capacity and Strategy Selection

We were interested in determining whether age-related differences in strategy selection behavior could be explained by cognitive capacity measures. Because strategy classification was a dichotomous variable, we performed a series of logistic regressions to investigate the relation between strategy selection and cognitive capacity. First, we estimated a set of logistic regression models using the strategy selected by the participants as the dependent variable (with the TTB/Take Two group as a base) and age or each cognitive capacity measure as a predictor. Second, the combined effect of age and cognitive capacity was considered. Improvements in prediction were tested by comparing "restricted" and "complete" logistic regressions using a log-likelihood ratio test (Cohen et al., 2003, p. 504). The fit of each logistic regression model is defined by the G^2 measurement (e.g., Burnham & Anderson, 1998), defined as −2 times the sum of the log likelihoods of the model. When two logistic regression models are nested, they can be compared via a log-likelihood ratio test, so that the G^2 of the simpler, restricted model is subtracted from the G^2 of the more complex, unrestricted model. The resulting difference is approximately chi-square distributed with the difference in number of free parameters as the degrees of freedom.

Results of the logistic regression analysis are summarized in Table 7. Overall, individual difference measures seem to account for age-related differences in strategy selection. The odds ratio concerning the effect of age is below 1 ($p < .01$), which reflects older adults' greater tendency to rely on the simpler TTB and Take Two strategies (vs. WADD) compared with young adults. Concerning the effect of cognitive capacity, the odds ratios above 1 ($p < .01$) concerning speed, reasoning, and memory factors indicate that higher scores on these were associated with using the more cognitively demanding WADD strategy compared with the TTB and Take Two strategies. Finally, Step 2 in Table 7 shows that adding age to a model including speed, reasoning, or memory factors as predictors did not improve the fit significantly. Including years of education or environment as predictors in the logistic regression models did not change the general pattern of results. In an additional regression model in which speed, reasoning, and memory factors were included as predictors, only reasoning proved to be a predictive factor: exp(B) = 1.00, p = .97, speed; exp(B) = 1.07, $p < .01$, reasoning; exp(B) = 1.02, p = .52, memory. In sum, individual differences in reasoning, a measure of fluid intelligence, account for all age-related differences in strategy selection, suggesting that older adults' increased reliance on simpler strategies is due to age-related decline in fluid intelligence.

Discussion

What is the impact of cognitive aging on the selection of decision strategies? To help answer this question, we examined how young and older adults inferred which of two alternatives had a higher criterion value on the basis of several cues. Our study varied the structure of the decision environment, such that in one condition, all cues had equal predictive power, and in the other, the cues' predictive power differed substantially. This manipulation created one environment that would favor the selection of a cog-

Table 7
Hierarchical Logistic Regressions with Strategy Classification as the Dependent Variable

Variable	Model deviance	G^2	p	Exp(B) Odds ratio
Step 1				
Age	199.2	9.20	<.01	0.98
Knowledge	208.3	0.09	.76	1.01
Speed	198.5	9.86	<.01	1.06
Reasoning	188.1	20.25	<.01	1.08
Memory	199.1	9.31	<.01	1.06
Step 2				
Knowledge + age	198.1	10.23	<.01	1.02
Speed + age	197.9	0.68	.41	1.03
Reasoning + age	188.1	0.05	.83	1.08
Memory + age	196.3	2.83	.09	1.04

Note. In Step 1, *Exp*(B) corresponds to the age coefficient or the cognitive capacity coefficients. In Step 2, G^2 represents the difference between the G^2 of the model with age and each capacity as predictors and that of the model with only capacity as predictor.

nitively demanding compensatory strategy and a second environment in which simpler strategies would do well. Participants' decisions were compared with the predictions of three strategies—the compensatory strategy WADD, and two simpler strategies, TTB and Take Two—to determine whether young and older adults chose appropriate strategies as a function of environmental structure when they did not have the opportunity to learn from outcome feedback. We examined how age-related differences were associated with differences in information search and strategy selection, and, in turn, how these were related to individual differences in cognitive functioning, such as fluid and crystallized abilities.

Overall, strategy selection was moderated by the environmental structure that the participants encountered: Both young and older adults appropriately selected the simpler strategies more often in the unequal validities environment compared with the equal validities environment. Thus, older adults did not always rely on simpler strategies but were adaptive in their strategy selection. This finding is compatible with the idea that young and older adults have an equally good understanding of strategy–environment correspondence. One possibility that we raised on the basis of reports in the aging literature (Baltes et al., 1999) was that older adults could have an advantage in adaptive strategy selection because of their richer knowledge of the strategy–environment correspondence. We reasoned that such an advantage would imply that crystallized intelligence should be a good predictor of adaptive strategy selection. However, our results show virtually no relation between measures of crystallized intelligence and decision behavior. One possibility is that our measures of crystallized intelligence do not tap into the relevant knowledge. Baltes et al. (1999) distinguished between normative knowledge, associated with formal schooling and more idiosyncratic person/domain-specific knowledge. Arguably, we have measured only normative knowledge, which may not be indicative of a person's understanding of strategy–environment correspondence. However, the pattern of results we observed is more in line with the view that older adults selected the simpler strategies more frequently out of necessity; they simply did not have the cognitive resources to use the more cognitively intensive WADD: Measures of fluid intelligence (i.e., reasoning) could account for the age-related differences in both information search and strategy selection, suggesting that older adults relied on simpler strategies due to age-related decline in fluid abilities.

Relation to Previous Findings

Past research in decision making has investigated which task characteristics, such as number of alternatives and attributes, influence strategy selection (Ford et al., 1989), the dispersion of the winning probabilities in gambles (Payne et al., 1993), time pressure (Svenson & Maule, 1993), and environment structure (Bröder, 2003; Rieskamp & Otto, 2006). Overall, the work suggests that people do behave adaptively; that is, they are able to select appropriate strategies as a function of task characteristics. Hence, people are usually described as adaptive decision makers (Beach & Mitchell, 1978; Payne et al., 1993). The results of our study add to the existing body of research in that they show that adaptivity can be observed even in the absence of extensive performance feedback and for both young and older adults.

Previous research on the impact of aging on decision-making abilities has provided a good description of age-related differences in comprehension of decision problems and has showed that these are related to individual differences in fluid intelligence (e.g., Finucane et al., 2002, 2005). Our study explored the impact of aging on information integration. In particular, we investigated the strategies used to integrate cue values and arrive at an inference. We found that older adults relied on less information, which is consistent with previous results found in preferential choice (e.g., Johnson, 1990, 1993). Moreover, in the present work, we conducted a comprehensive assessment of cognitive ability and assessed the relation between ability and strategy selection. A major finding is that fluid intelligence—in particular, reasoning abilities—but not crystallized intelligence accounted for the age-related variance in strategy selection: Older adults' age-related decline in fluid intelligence seems to be related to their increased reliance on simpler strategies.

Our results are seemingly at odds with Bröder's (2003) findings on the relation between cognitive ability and strategy selection in young adults, which suggests that higher scores on fluid intelligence measures may be related to increased reliance on simpler strategies: Young adults with higher scores on a reasoning measure were more likely to select simpler strategies in the appropriate environment. However, Bröder observed this relation in inference situations in which participants learned the structure of the environment through extensive outcome feedback, suggesting that the effect of reasoning in Bröder's work may be associated with the ability to learn the structure of the environment and strategy–environment contingencies. In contrast, in our study, which did not involve learning through outcome feedback, the effect of reasoning seems to be related to people's abilities to use cognitively demanding strategies. Support for this interpretation is that other measures of fluid intelligence (e.g., memory) were also negatively correlated with the use of simpler strategies in our study but unrelated to strategy selection in Bröder (2003).

There is a close connection between our effort to understand how cognitive aging impacts adaptive selection of decision strategies and research in the arithmetic domain. For example, Lemaire et al. (2004) investigated the ability of young and older adults to select strategies as a function of arithmetic problem type and found that older adults were able to adapt to task characteristics but were in general worse in their strategy selection and application. Likewise, in our study, older adults were adaptive, adjusting their strategy selection as a function of task characteristics, but they tended to rely more often on simpler strategies than did the young adults. Overall, these results provide a picture of the aging decision maker as an adaptive one but challenged by increased cognitive limitations.

Implications for Models of Strategy Selection

Our results should encourage more detailed models of strategy selection processes, particularly at the computational level. Computational models may be particularly useful in exposing the impact of aging on learning processes in strategy selection (Rieskamp & Otto, 2006; Siegler & Lemaire, 1997). For example, the strategy selection learning theory (Rieskamp & Otto, 2006) in its extended version includes a forgetting parameter that could be used to make predictions about age-related deficits in strategy selection. In addition, results from aging research may help extend the existing models.

For the sake of parsimony, Rieskamp and Otto (2006) defined the reinforcements that govern the selection of strategies in purely monetary terms. Our study illustrates that this simplification should not be used when comparing older and young adults. Here the cognitive costs of processing a strategy become a crucial factor that should be taken into account. Thus, it is more appropriate to define the strategies' reinforcements as a compound consisting of a strategy's accuracy, its costs for acquiring information, and its application costs. These different components may be weighted differently depending on the cognitive capacities of the decision maker. For example, individuals with lower cognitive capacities may give larger weight to the application costs, which will lead to the selection of simpler strategies. Testing such an extension to the strategy selection learning theory could help elucidate the processes underlying strategy selection and associated age-related changes.

Applied Potential of Understanding the Aging Decision Maker

The main goal of our study was to contribute to the understanding of the relation between decision making and cognitive aging. However, there is applied potential in the knowledge gained from the study of age-related change in decision making. Our results suggest that older adults may rely on simpler strategies more often than do young adults. Ecological rationality (cf. Gigerenzer et al., 1999)—that is, the correspondence between strategies and specific environments—can explain when these simple strategies give accurate solutions to a problem and when they fail. For example, our study included an environment in which the use of simpler strategies was appropriate, thus matching older adults' preference for simpler strategies. Similarly, simple strategies are well suited for making predictions based on noisy or unreliable information, such as estimating the relation between a cue and a criterion based on a small sample. One interesting possibility is that older adults' use of simpler strategies would give them an advantage in these noisy conditions. Identifying the conditions in which simple strategies do well and training older adults to select these strategies in the appropriate situation could help them achieve higher levels of functioning (Kramer & Willis, 2002).

Our work and the comparison with previous and future findings could be particularly useful in designing real-world applications. Previous studies found age-related differences in situations with considerable information overload (e.g., Johnson, 1990, 1993). We showed age-related differences in which only two options had to be processed, but cues were inspected sequentially and only once, which may have considerably taxed working-memory. Future studies should quantify how age differences in information search and strategy selection may be eliminated as a function of different task characteristics, such as the amount of information to be considered, the type of information presentation (sequential vs. simultaneous), and the existence of decision aids designed to deal with potential memory limitations. Internet-based decision-support systems that usually involve a large number of options and associated attributes, and thus make the process of deciding between alternatives cumbersome (Fasolo, McClelland, & Todd, 2007), could then take these results into consideration in their design.

Conclusion

Researchers in decision making (Gigerenzer et al., 1999; Payne et al., 1993) and aging (Baltes & Baltes, 1990) conceptualize adaptive behavior as the result of a balance between individual potential and the demands and resources provided by the environment. Our work reflects this position by characterizing aging decision makers as adaptively selecting strategies as a function of their cognitive resources and task characteristics, such as the statistical structure of environments. The focus on environmental structure delivers another important insight: Older adults' increased reliance on less cognitively demanding strategies may not always be a drawback, as these simpler strategies may fit particular environments. We hope this thought will encourage researchers in cognitive aging to study the potential of simple heuristics in decision making as well as other domains.

References

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2002). Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. *Journal of Experimental Psychology: General, 131,* 567–589.

Baltes, P. B., & Baltes, M. M. (1990). Psychological perspectives on successful aging: The model of selective optimization with compensation. In P. B. Baltes & M. M. Baltes (Eds.), *Successful aging: Perspectives from the behavioral sciences* (pp. 1–34). New York: Cambridge University Press.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12,* 12–21.

Baltes, P. B., Reese, H. W., & Nesselroade, J. R. (1988). *Life-span developmental psychology: Introduction to research methods.* Hillsdale, NJ: Erlbaum.

Baltes, P. B., Staudinger, U. M., & Lindenberger, U. (1999). Lifespan psychology: Theory and application to intellectual functioning. *Annual Review of Psychology, 50,* 471–507.

Beach, L. R., & Mitchell, T. R. (1978). A contingency model for the selection of decision strategies. *Academy of Management Review, 3,* 439–449.

Bröder, A. (2000). Assessing the empirical validity of the "Take The Best"-heuristic as a model of human probabilistic inference. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1332–1346.

Bröder, A. (2003). Decision making with the "adaptive toolbox": Influence of environmental structure, intelligence, and working memory load. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 29,* 611–625.

Burnham, K. P., & Anderson, D. R. (1998). *Model selection and inference: A practical information-theoretic approach.* New York: Springer.

Chasseigne, G., Ligneau, C., Grau, S., Le Gall, A., Roque, M., & Mullet, E. (2004). Aging and probabilistic learning in single-and multiple-cue tasks. *Experimental Aging Research, 30,* 23–45.

Chen, Y., & Sun, Y. (2003). Age differences in financial decision-making: Using simple heuristics. *Educational Gerontology, 29,* 627–635.

Christensen-Szalanski, J. J. (1978). Problem solving strategies: A selection mechanism, some implications, and some data. *Organizational Behavior and Human Decision Processes, 22,* 307–323.

Cohen, G., & Faulkner, D. (1983). Word recognition: Age differences in contextual facilitation effects. *British Journal of Psychology, 74,* 239–251.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). *Applied multiple regression/correlation analysis for the behavioral sciences.* Hillsdale, NJ: Erlbaum.

Coyle, T. R., Read, L. E., Gaultney, J. F., & Bjorklund, D. F. (1998). Giftedness and variability in strategic processing on a multitrial memory task: Evidence for stability in gifted cognition. *Learning and Individual Differences, 10,* 273–290.

Dieckmann, A., & Rieskamp, J. (in press). The influence of information redundancy on probabilistic inferences. *Memory & Cognition.*

Dunlosky, J., & Hertzog, C. (1998). Aging and deficits in associative memory: What is the role of strategy use? *Psychology and Aging, 13,* 597–607.

Dunlosky, J., & Hertzog, C. (2000). Updating knowledge about encoding strategies: A componential analysis of learning about strategy effectiveness from task experience. *Psychology and Aging, 15,* 462–474.

Einhorn, H. J. (1970). The use of nonlinear, noncompensatory models in decision making. *Psychological Bulletin, 73,* 221–230.

Fasolo, B., McClelland, G. H., & Todd, P. M. (2007). Escaping the tyranny of choice: When fewer attributes make choice easier. *Marketing Theory, 7,* 3–26.

Finucane, M. L., Mertz, C. K., Slovic, P., & Schmidt, E. S. (2005). Task complexity and older adults' decision-making competence. *Psychology and Aging, 20,* 71–84.

Finucane, M. L., Slovic, P., Hibbard, J., Peters, E., Mertz, C. K., & MacGregor, D. G. (2002). Aging and decision-making competence: An analysis of comprehension and consistency skills in older versus younger adults considering health-plan options. *Journal of Behavioral Decision Making, 15,* 141–164.

Ford, J. K., Schmitt, N., Schechtman, S. L., Hults, B. M., & Doherty, L. (1989). Process tracing methods: Contributions, problems, and neglected research questions. *Organizational Behavior and Human Decision Processes, 43,* 75–117.

Geary, D. C., Frensch, P. A., & Wiley, J. G. (1993). Simple and complex mental subtraction: Strategy choice and speed-of-processing differences in younger and older adults. *Psychology and Aging, 8,* 242–256.

Geary, D. C., & Wiley, J. G. (1991). Cognitive addition: Strategy choice and speed-of-processing differences in young and elderly adults. *Psychology and Aging, 6,* 474–483.

Gigerenzer, G. (2003). The adaptive toolbox and life span development: Common questions? In U. M. Staudinger & U. E. R. Lindenberger (Eds.), *Understanding human development: Life span psychology in exchange with other disciplines* (pp. 423–435). Dordrecht, The Netherlands: Kluwer.

Gigerenzer, G., & Goldstein, D. G. (1996). Reasoning the fast and frugal way: Models of bounded rationality. *Psychological Review, 103,* 650–669.

Gigerenzer, G., & Selten, R. (2001). *Bounded rationality.* Cambridge, MA: MIT Press.

Gigerenzer, G., Todd, P. M., & the ABC Research Group. (1999). *Simple heuristics that make us smart.* New York: Oxford University Press.

Hamm, S. (2002). AG-Spanne: Validierung eines deutschsprachigen Verfahrens zur Erfassung der Arbeitsgedächtnisspanne. [AG-Spanne: Validation of a technique for assessing the working memory span in the German language]. *Berichte aus dem Psychologischen Institut der Universität Bonn, 28*(2).

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica, 26,* 107–129.

Huber, O. (1980). The influence of some task variables on cognitive operations in an information-processing decision model. *Acta Psychologica, 45,* 187–196.

Johnson, M. M. S. (1990). Age differences in decision making: A process methodology for examining strategic information processing. *Journal of Gerontology, 45,* 75–78.

Johnson, M. M. S. (1993). Thinking about strategies during, before, and after making a decision. *Psychology and Aging, 8,* 231–241.

Johnson, M. M. S., & Drungle, S. C. (2000). Purchasing over-the-counter medications: The impact of age differences in information processing. *Experimental Aging Research, 26,* 245–261.

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 336–358.

Kim, S., & Hasher, L. (2005). The attraction effect in decision making: Superior performance by older adults. *Quarterly Journal of Experimental Psychology, 58A,* 120–133.

Kovalchik, S., Camerer, C. F., Grether, D. M., Plott, C. R., & Allman, J. M. (2005). Aging and decision making: A comparison between neurologically healthy elderly and young individuals. *Journal of Economic Behavior & Organization, 58,* 79–94.

Kramer, A. F., & Willis, S. L. (2002). Enhancing the cognitive vitality of older adults. *Current Directions in Psychological Science, 11,* 173–177.

Lemaire, P., Arnaud, L., & Lecacheur, M. (2004). Adults' age-related differences in adaptivity of strategy choices: Evidence from computational estimation. *Psychology and Aging, 10,* 467–481.

Lemaire, P., & Siegler, R. S. (1995). Four aspects of strategic change: Contributions to children's learning of multiplication. *Journal of Experimental Psychology: General, 124,* 83–97.

Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Lifespan transformations in the couplings of mental abilities and underlying cognitive processes. *Psychological Science, 15,* 155–163.

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8,* 207–220.

Lindenberger, U., & Pötter, U. (1998). The complex nature of unique and shared effects in hierarchical linear regression: Implications for developmental psychology. *Psychological Methods, 3:* 218–230.

Mather, M. (2006). A review of decision making processes: Weighing the risks and benefits of aging. In L. L. Carstensen & C. R. Hartel (Eds.), *When I'm 64* (pp. 145–173). Washington, DC: National Academies Press.

Newell, B. R., & Shanks, D. R. (2003). Take the best or look at the rest? Factors influencing "one-reason" decision making. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 53–65.

Payne, J. W. (1976). Task complexity and contingent processing in decision making: An information search and protocol analysis. *Organizational Behavior and Human Performance, 16,* 366–387.

Payne, J. W., Bettman, J. R., & Johnson, E. J. (1988). Adaptive strategy selection in decision making. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 14,* 534–552.

Payne, J. W., Bettman, J. R., & Johnson, E. J. (1993). *The adaptive decision maker.* Cambridge, United Kingdom: Cambridge University Press.

Peters, E., Finucane, M. L., MacGregor, D. G., & Slovic, P. (2000). The bearable lightness of aging: Judgment and decision processes in older adults. In National Research Council, P. C. Stern, & L. L. Carstensen (Eds.), *The aging mind: Opportunities in cognitive research* (Appendix C, pp. 144–165). Washington, DC: National Academies Press.

Rieskamp, J. (2006). Perspectives of probabilistic inferences: Reinforcement learning and an adaptive network compared. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 32,* 1371–1384.

Rieskamp, J., & Hoffrage, U. (1999). When do people use simple heuristics, and how can we tell? In G. Gigerenzer, P. M. Todd, & the ABC Research Group, *Simple heuristics that make us smart* (pp. 141–167). New York: Oxford University Press.

Rieskamp, J., & Hoffrage, U. (in press). Inferences under time pressure: How opportunity costs affect strategy selection. *Acta Psychologica.*

Rieskamp, J., & Otto, P. (2006). SSL: A theory of how people learn to select strategies. *Journal of Experimental Psychology: General, 135,* 207–236.

Riggle, E. D. B., & Johnson, M. M. S. (1996). Age differences in political decision making: Strategies for evaluating political candidates. *Political Behavior, 18,* 99–118.

Salthouse, T. A. (1991). *Theoretical perspectives on cognitive aging.* Hillsdale, NJ: Erlbaum.

Sanfey, A. G., & Hastie, R. (1999). Judgment and decision making across the adult life span. In D. Park & N. Schwarz (Eds.), *Aging and cognition: A primer.* Philadelphia: Psychology Press.

Schunn, C. D., & Reder, L. M. (2001). Another source of individual differences: Strategy adaptivity to changing rates of success. *Journal of Experimental Psychology: General, 130,* 59–76.

Siegler, R. S., & Lemaire, P. (1997). Older and younger adults' strategy choices in multiplication: Testing predictions of ASCM via the choice/no choice method. *Journal of Experimental Psychology: General, 126,* 71–92.
Simon, H. A. (1956). Rational choice and the structure of the environment. *Psychological Review, 63,* 129–138.
Svenson, O. (1979). Process descriptions of decision making. *Organizational Behavior and Human Performance, 23,* 86–112.
Svenson, O., & Maule, J. A. (Eds.). (1993). *Time pressure and stress in human judgment and decision making.* London: Plenum Press.
Thornton, W. J. L., & Dumke, H. (2005). Age differences in everyday problem solving and decision making effectiveness: A meta-analytic review. *Psychology and Aging, 20,* 85–99.
Wechsler, D. (1981). *Wechsler Adult Intelligence Scale: Revised Manual (WAIS-R).* New York: Psychological Corporation.
Wilson, R. S., Beckett, L. A., Barnes, L. L., Schneider, J. A., Bach, J., Evans, D. A., & Bennett, D. A. (2002). Individual differences in rates of change in cognitive abilities of older persons. *Psychology and Aging, 17,* 179–193.
Wood, S., Busemeyer, J., Koling, A., Cox, C. R., & Davis, H. (2005). Older adults as adaptive decision makers: Evidence from the Iowa Gambling Task. *Psychology and Aging, 20,* 220–225.

Appendix

Model Recovery Analysis of the Accuracy of Classification Methods

We used model recovery techniques to test the adequacy of different classification procedures. Model recovery techniques involve (a) generating data on the basis of a known process or distribution, usually adding some variance to its outcome and (b) using some method of interest to identify the underlying structure of the data and comparing it to the known distribution underlying the data to obtain an estimate of the accuracy of the recovery process. The general strategy adopted was to determine how successful outcome-only, search-only, and outcome-and-search classification methods are at uncovering the strategies used by simulated participants. By using simulated participants, one is able to control the underlying distribution of strategy users and thus quantify the success of different methods in recovering the true state of events. Naturally, if participants perfectly apply a particular strategy throughout all trials all classification methods should be equivalent. However, people make errors when applying decision strategies and thus one should ask whether the different classification methods are equally reliable when considering different distributions and types of errors, such as errors in reading and comparing information, or in making a decision.

Data Generation

We first generated data for a number of simulated participants using one of three strategies: TTB, Take Two, and WADD. We incorporated strategy application errors by assuming that with a specific probability, the necessary elementary information processes (EIPs) of a strategy were performed incorrectly. The following EIPs were performed: (a) a storing process (READ), responsible for storing cue values in working memory, (b) a retrieval process (COMPARE), responsible for the retrieval and comparison of values in working memory, and (c) a decision process (DECIDE), responsible for the choice of a particular option. The probability with which an EIP was performed incorrectly at each time step was varied from .05 to .25. An error in the storing process led to storing a cue value as 1 when it was in fact 0, and vice versa. An error in the retrieval process consisted of not being able to see a difference between options: This led TTB and Take Two either to look up another cue if one was available or to guess if it was not; for WADD, which compares the values of the tallies of the two options after looking up all information, such a mistake always led to guessing. Finally, an error in the decision process led to the opposite choice as predicted by the strategy. For simplicity, errors in different components occurred with equal probability. The simulated participants' responses corresponded to the algorithms' responses to data from randomly selected input samples from our study.

Data Recovery

Following the data generation, we used an outcome-only, a search-only, and an outcome-and-search classification method to classify participants as users of a particular strategy. The outcome-only classification procedure involved counting for each participant the number of inferences for which the final choice corresponded to the one predicted by the different strategies. The search-only classification procedure involved counting for each participant the number of inferences for which the information search (i.e., number of cues searched) corresponded to that predicted by the different strategies. The outcome-and-search classification involved counting for each participant the number of inferences for which the information search *and* the final choice corresponded to the predicted search and choice of the different strategies. In all methods, the strategy that predicted the most inferences correctly for a simulated participant was assigned to it.

Table A1 shows the proportion of classified simulated participants as a function of the generating strategy and error rate. Each row is based on 10,000 simulated patterns. The results can be summarized as follows: The accuracy of the outcome-only classification method is sensitive to application errors; percentage of correct classifications drops substantially with increasing error rate regardless of whether the generating strategy is TTB, Take Two, or WADD. In contrast, the two classifications that consider search do not seem to be affected with increased probability of application errors regardless of error rate and strategy (with the exception of Take Two). In sum, classifications that take search into account seem to be superior to outcome-only classifications.

(*Appendix continues*)

Table A1
Percentage of Classifications as a Function of Generating Strategy and Error Rate

Generating strategy	Error rate	Classification			
		TTB	Take Two	WADD	Unclassified
		Outcome-only classification			
TTB	.05	**100**	—	—	—
	.10	**87**	7	5	1
	.25	**58**	21	15	6
Take Two	.05	1	**94**	1	4
	.10	12	**40**	30	18
	.25	22	**26**	37	15
WADD	.05	—	—	**99**	1
	.10	10	8	**71**	11
	.25	25	18	**44**	13
		Search-only classification			
TTB	.05	**100**	—	—	—
	.10	**100**	—	—	—
	.25	**100**	—	—	—
Take Two	.05	—	**100**	—	—
	.10	—	**100**	—	—
	.25	—	**87**	8	5
WADD	.05	—	—	**100**	—
	.10	—	—	**100**	—
	.25	—	—	**100**	—
		Outcome-and-search classification			
TTB	.05	**100**	—	—	—
	.10	**100**	—	—	—
	.25	**100**	—	—	—
Take Two	.05	—	**100**	—	—
	.10	—	**100**	—	—
	.25	—	**87**	7	6
WADD	.05	—	—	**100**	—
	.10	—	—	**100**	—
	.25	—	—	**100**	—

Note. Percentages of accurate classifications are presented in bold. TTB = Take The Best; WADD = weighted additive rule.

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