# Development of decision making based on internal and external information: A hierarchical Bayesian approach

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**Abstract**

In decision making, people may rely on their own information as well as on information from external sources, such as family members, peers, or experts. The current study investigated how these types of information are used by comparing four decision strategies: 1) an internal strategy that relies solely on own information; 2) an external strategy that relies solely on the information from an external source; 3) a sequential strategy that relies on information from an external source only after own information is deemed inadequate; 4) an integrative strategy that relies on an integration of both types of information. Of specific interest were individual and developmental differences in strategy use. Strategy use was examined via Bayesian hierarchical mixture model analysis. A visual decision task was administered to children and young adolescents (N=305, ages 9–14). Individual differences but no age-related changes were observed in either decision accuracy or strategy use. The internal strategy was dominant across ages, followed by the integrative and sequential strategy, respectively, while the external strategy was extremely rare. This suggests a reluctance to rely entirely on information provided by external sources. We conclude

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that there are individual differences but not developmental changes in strategy use pertaining to perceptual decision-making in 9- through 14-year-olds. Generalizability of these findings is discussed with regard to different forms of social influence and varying perceptions of the external source. This study provides stepping stones in better understanding and modeling decision making processes in the presence of both internal and external information.

Keywords: decision making, information processing, Bayesian hierarchical mixture, development, social influence

# 1 Introduction

When making decisions people may rely on their own information, that is, "internal information", as well as on information provided by others, that is, "external information". For example, a person may decide by themselves how to vote in an election but they may also inquire how others vote and vote accordingly. Similarly, a student taken a multiple-choice exam may answer all questions on their own merit or they may cheat off of the student next to them. External information may benefit decision making by adding relevant knowledge (Apesteguia, Huck & Oechssler, 2007; Hertz & Wiese, 2016, 2018; Morgan et al., 2012; Morgan et al., 2015) but it can be harmful when the source of external information is less knowledgeable than, or has priorities misaligned with those of the decision maker (Byrne et al., 2016; Crawford et al., 2002).

Decision making involving internal and external information varies between individuals, which has been attributed to individual differences in strategy use (Mesoudi et al., 2016; Molleman et al., 2020; Molleman, Van Den Berg & Weissing, 2014). In this context, strategies are qualitatively distinct mechanisms of using internal or external information to reach a decision. Understanding the effects of internal and external information use in the population is relevant to a variety of real-world settings such as political party voting (Stewart et al., 2019), court jury rulings (Levett & Devine, 2017; Kovera et al., 1997; Moore & Gump, 1995), economic drifts and marketing tactics (Aral & Walker, 2014; Devenow & Welch, 1996), and the spread of knowledge in social networks (Bakshy et al., 2012).

We wish to thank all participants, parents or guardians, and school staff that have aided in making these studies possible. Also, we thank Lucas Molleman for his valuable suggestions. We also wish to thank the reviewers and editor, Michael Lee, for their valuable input. Finally, we thank the following for assistance in data collection: Rosemarijn van Beek, Fay Cleaver, Pauline Dijkstra, Ihwanti van Hulst, Iris van der Hut, Romy van Jaarsveld, Liza Klouwers, Anne-Wil Kramer, Hester van der Lely, Robin van der Reep, Odette van Rongen, Carlijn Vrijhoef.

Funding details: this work was supported by a VICI grant [number 453–12–005]. The funding source was not in any way involved with the research.

Codes and output can be found at https://osf.io/pe8jw/?view_only=4c3e221a699f475280b28f361206bcd5.

In this paper we cover four decision strategies. According to the first two strategies people consider only one type of information, translating to an internal information strategy — i.e., a strategy of relying solely on internal information while ignoring external information — or an external information strategy — i.e., a strategy of relying solely on external information. Yet, most people consider both internal and external information when making decisions (Mesoudi et al., 2016; Molleman et al., 2020, 2014). We propose two more strategies to account for this.

The first is the integrative strategy, in which internal and external information are integrated to reach a decision (Molleman et al., 2020). This strategy is comparable to compensatory decision rules (Jansen et al., 2012; Rothrock & Yin, 2008; Shiloh et al., 2001; Van Duijvenvoorde et al., 2016) or weighted-additive decision strategies (Payne et al., 1988). Decisions are based on the weighted sum of all choice attributes, in this case internal and external information. Thus, each decision is informed by internal and external information simultaneously.

The second strategy is the sequential strategy in which individuals rely on external information only after internal information is deemed insufficiently discriminant between choice options; i.e., when the decision is deemed too difficult. This strategy is comparable to the *take-the-best* (TTB) heuristic, which dictates sequential consideration of available information in order of importance until a sufficiently informative piece of information is encountered (Gigerenzer, 1999; Gigerenzer & Gaissmaier, 2011; Lee & Cummins, 2004). Decisions are thus based on either internal or external information as a function of decision difficulty. For example, a quiz show contestant being asked to decide whether a golf ball or a basketball is larger, is unlikely to seek out external information before responding. However, that same contestant being asked whether Nigeria or Tanzania is larger, is likely to seek advice (when that is permitted). This sequential mechanism matches observations that people generally prefer internal information in decision making (Toelch et al., 2014), but rely increasingly on external information as decisions become more difficult (Beckner et al., 2016; Hertz & Wiese, 2016, 2018; Morgan, Rendell, Ehn, Hoppitt & Laland, 2012; Morgan, Laland & Harris, 2015). Internal information being considered first reflects the common finding that people value their own information more than that of external sources (Morgan et al., 2015; Yaniv, 2004; Yaniv & Kleinberger, 2000).

Similar to how differences in strategy use could explain *individual* differences in decision making, it may also explain *age* differences in decision making. Adolescence appears a developmental period of heightened susceptibility to external information, marked by increased risk taking through peer pressure (Bednar & Fisher, 2003; Blakemore & Robbins, 2012; Dekkers et al., 2018; Gardner & Steinberg, 2005; Steinberg, 2008; Sumter et al., 2009; Zwane et al., 2004). Additionally, external information has been observed to start influencing the decision process *additional to* internal information around age 12 (Large et al., 2019). This suggests an age-related increase in sequential or integrative strategy use between childhood and adolescence. To examine this, we test the presence of an age-related increase in either sequential or integrative strategy use in 9- to 14-year-olds.

For the purposes of our study it is relevant to distinguish between decision strategies and strategy parameters. Strategies represent mechanisms describing *how* internal or external information are used in decision making, while strategy parameters denote the *extent* to which these types of used information influence decision making. Differences in strategy parameters may explain differences in decision behavior irrespective of, or in combination with strategy use. For example, the impact of external information on decision behavior being more pronounced in some individuals than others may be explained by the use of the integrative instead of internal strategy. However, such decision-making differences may also be due to differences in the extent to which eternal information influences decisions. For example, some integrative strategy users may rely more heavily on external information than others. By distinguishing between strategies and strategy parameters we prevent mistaking one for the other as explanatory of variability in decision behavior.

To summarize, we investigate four decision strategies to explain individual and developmental differences in the role of internal or external information in decision making. Describing possible roles are the internal information strategy (from now on: "internal strategy"), the external information strategy (from now on: "external strategy"), the sequential strategy, and the integrative strategy. Many studies have focused on the influence of external sources on decision making (Albert & Steinberg, 2011; Brandstetter et al., 2014; Carr et al., 2015; Cutler et al., 1989; Gardner & Steinberg, 2005; Kim & Srivastava, 2007; Lee et al., 2011; Mesoudi et al., 2016; Moschis & Moore, 1997; Sawyer & Stevenson, 2008; van 't Wout & Sanfey, 2008), how this changes with age (Larg et al., 2019; Morgan et al., 2015; Rolison et al., 2017), and on underlying strategies (Molleman et al., 2020). The current study is the first to combine these three aims, examining the aforementioned strategies as well as strategy parameters with respect to age. Specifically, we examine the transition between childhood and adolescence. Increased sequential or integrative strategy use is expected in adolescence relative to childhood.

To examine individual differences and age-related differences in strategy use, we administered a perceptual decision-making task entailing a choice between two stimuli. External information came in the form of a hint concerning the correct response. Decisions were modelled by means of formalized strategy models as implemented in a Bayesian hierarchical mixture analysis.

# 2 Methods

The goal of this study was to determine how internal or external information were used in decision making, as well as to assess individual and potential age-related differences in internal or external information use. A pilot study is described in Supplement F.

#### 2.0.1 Participants

A total of 334 participants between the ages of 8 and 15 ($M_{age}$ = 11.6, $sd$ = 1.6), of which 155 were male, took part in the research. Six 8- and 15-year-olds were omitted from analyses as their numbers were too small to represent their age population accurately. Recruitment happened via schools, which were approached via email or phone, or a pre-existing contact. The school sent an information brochure and passive informed consent form to the respective parents/caretakers, who needed only to reply if participation of the child was denied.

A total of 10 schools agreed to participate. Participants were collected from the last three grades of primary school and the first two grades of secondary school, across education levels.[1] As a participation reward, five bags of sweets or chocolate bars were randomly distributed per class, but only among students who behaved as instructed (i.e., no talking, no cheating, no finishing in under 5 minutes). Participants were omitted from analyses if they failed to respond to >10% of items.

### 2.1 Materials

#### 2.1.1 Participant form

Demographic information was collected via several multiple-choice questions. We measured the following variables: pertaining to age in years, sex, grade, and school level (primary school, or secondary school with levels: low/middle/high).

#### 2.1.2 Perceptual decision task

Decision making was studied using a visual discrimination task with binary choice items. People were shown two lines with the objective to indicate which was longer, the single line ($L_1$) or the two separate line segments combined ($L_2$). The more $L_1$ and $L_2$ differed, the easier the item. $L_1$ was of constant length at 75mm while $L_2$ varied between 63.75mm and 86.25mm. Participants indicated which was longer by checking one of two response boxes at the bottom of the item. See Figure 1 for an example item, and Figure 2 for the visual aid included with task instructions. As the stimuli were never equal, "$L_1 = L_2$" was not a response option.

This task consisted of 120 items, a number sufficient for the intended strategy assignment analysis based on simulations. External information came in the form of hints, that is, two extra response boxes at the top of the item, one of which was already checked. These represented the responses of a supposed "Robin", who participants were told had completed the task in a pilot study answering 90 out of 120 items (75%) correctly. In reality, responses by "Robin" were simulated by the researchers. As in English, the name "Robin" is gender

[1]In the Netherlands, primary school runs from grades 3 to 8 (ages 6-12). In secondary school, grade numbering restarts at 1. Secondary school has three academic levels.

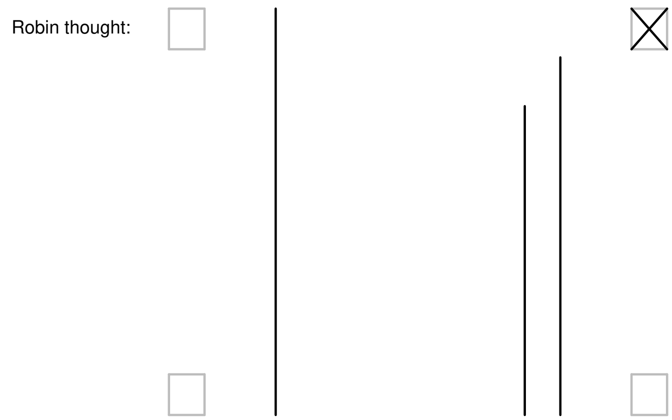


FIGURE 1: An example item of the visual decision task with hints. Here, the single vertical straight line — $L_1$ — is shown on the left, the two separate vertical line segments — together $L_2$ — on the right, with a corresponding response box on the bottom left and right. In this item $L_2$ is longer than $L_1$, meaning that checking the bottom right box indicates the correct response. At the top, two more boxes are displayed which indicate the answer of "Robin", i.e., the external information or "hint". The accompanying text reads "Robin thought:" in Dutch. The top right box has been checked, indicating the information provided by "Robin" that $L_2$ is longer than $L_1$. As this was an example item, it was purposefully easy to answer.

neutral in Dutch. The percentage of correct hints and the presentation format of the hints were based on the pilot study. The correctness percentage of 75% was chosen because it struck a balance between guessing — 50% correct, in which case there would be no logical reason to consider external information — and perfect discrimination — 100% correct, in which case there would be no reason to consider internal information.

The task was administered via an A4 booklet with four items per page. Items were presented in a randomized order so that the length of $L_2$ varied randomly. Items were varied to have $L_1$ and $L_2$ switch from left to right every other item, as to prevent responses biased towards either side. This was done only after the order of items was randomized. Items were created in R. Details on the task and item properties are given in Supplement A.

Both the task and instructions were in Dutch. Instructions were to provide a single response to each item, to use only their eyes to reach a decision, and to refrain from skipping back to previous pages. Early test administration showed the task to take between 8 and 12 minutes to complete.

## 2.2 Procedure

Test administration happened at the school, per class, overseen by at least two researchers and a teacher. Participants completed each subsection individually and on paper. Instructions were read aloud from the booklet with participants reading along, followed by practice with example items. The practice items included unambiguous decisions so that incorrect

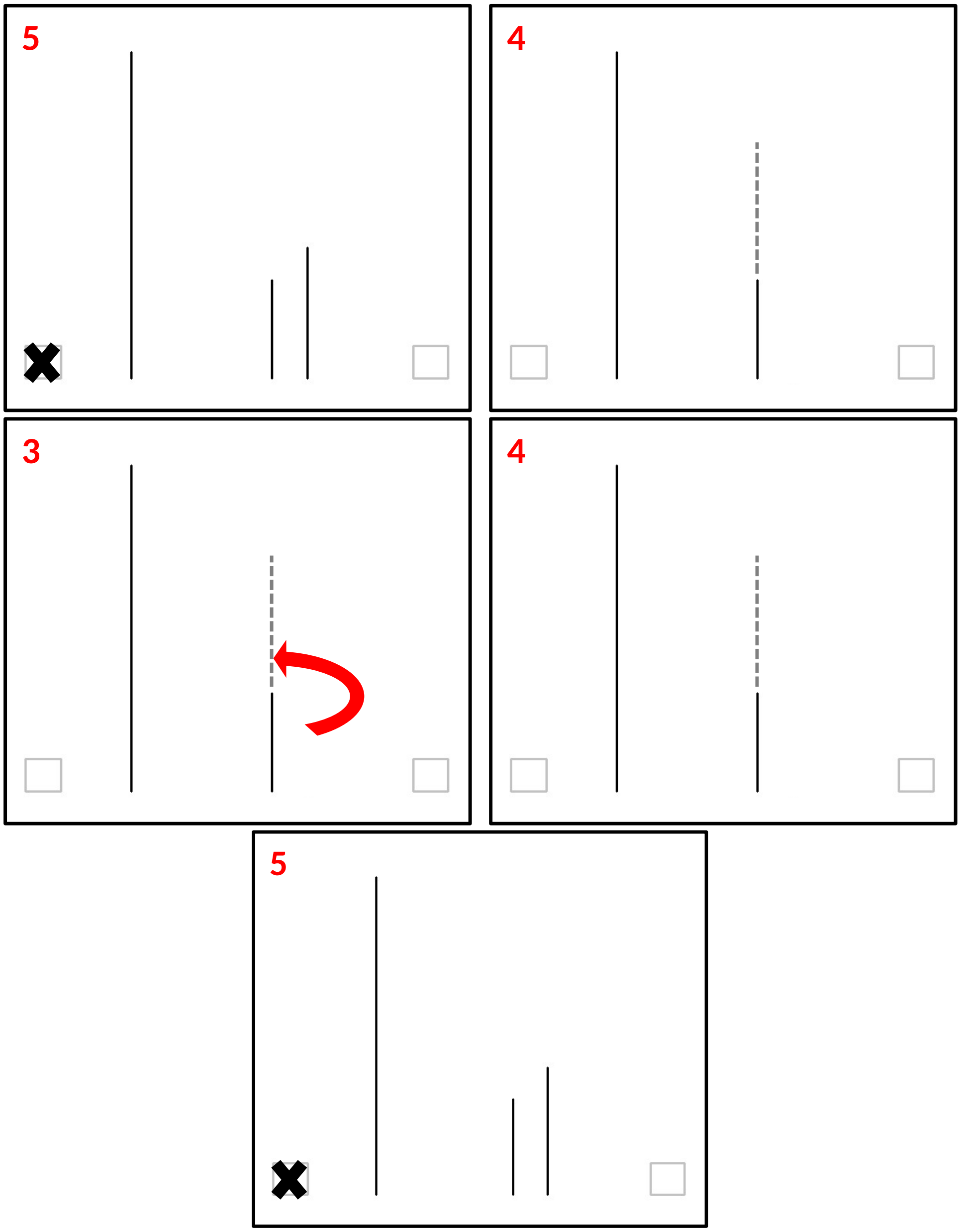


Figure 2: The visual aid alongside task instructions as included in the booklet. Written instructions read: “Here you see the same question as on the previous page (frame 1). We pretend as if we take one of the two lines and place it atop the other (frame 2 & 3). That way we can see that the single line is longer than the two lines combined (frame 4). That’s why we check the box of the single line (frame 5).”

answers would indicate miscomprehension of the task rather than inability, thus alerting the researcher that additional instructions were needed. At the end of the practice round, participants were told that the items of the real task would not be so easy. During the practice round, asking questions was encouraged. Questions could also be asked during task administration itself, albeit individually and quietly as not to disturb other participants.

The time limit for completing the decision task was 15 minutes. After this time, booklets were retrieved. Participants who finished early could entertain themselves with a provided booklet of puzzles (e.g., word riddles, connect-the-dots, Sudoku). Total test administration duration, including instructions and the break, was approximately 20 minutes.

Beforehand, participants and parents/caretakers were told that the research was aimed at measuring visual-spatial ability. After testing on a school was completed, a debriefing form was sent by the school to the parents/caretakers of participants, explaining the true research purpose and the reason for this deception. Retroactive withdrawal from the study was not possible as the data were collected completely anonymously due to privacy regulations.

## 2.3 Statistical Analyses

### 2.3.1 Decision Strategy Models

Decision task data were analyzed using seven models. The first four models represented the strategies of interest, namely the internal strategy, the external strategy, the sequential strategy, and the integrative strategy. The remaining three models represented strategies using neither internal or external information, namely the guessing model, the $L_1$ constant stimulus bias model, and the $L_2$ varying stimulus bias model. The latter were added to accommodate response patterns indicative of non-compliance to task instructions. All models are described below.

**The Internal Strategy Model.** According to the internal strategy model individuals base their decisions solely on internal information, see Figure 3, top left, and Equation 1.

$$P\left(R_{(ij)} = [L_{2(j)} > L_{1(j)}]\right) = \frac{1}{1 + e^{-(b_{int(i)} \times L_{\Delta(j)})}} \tag{1}$$

In this logistic regression, the probability of participant $i$ responding "$L_2 > L_1$" on item $j$ depends on internal information of item $j$, i.e., the standardized difference between $L_2$ and $L_1$, $L_\Delta$. The extent of this dependence is indexed by strategy parameter $b_{int(i)}$.

**The External Strategy Model.** The external strategy model predicts that individuals solely base decisions on external information, see Figure 3, top right, and Equation 2.

$$P\left(R_{(ij)} = [L_{2(j)} > L_{1(j)}]\right) = \frac{1}{1 + e^{-(b_{ext(i)} \times hint_{(j)})}}. \tag{2}$$

This logistic regression predicts the probability of participant $i$ responding "$L_2 > L_1$" on item $j$ using the external information of item $j$, $hint_{(j)}$. $hint_{(j)}$ was 1 when external information pointed towards the correct response being "$L_2 > L_1$" and $hint_{(j)}$ was $-1$ when external pointed towards " $L_2 < L_1$". The effect of external information on this response probability is denoted by strategy parameter $b_{ext(i)}$.

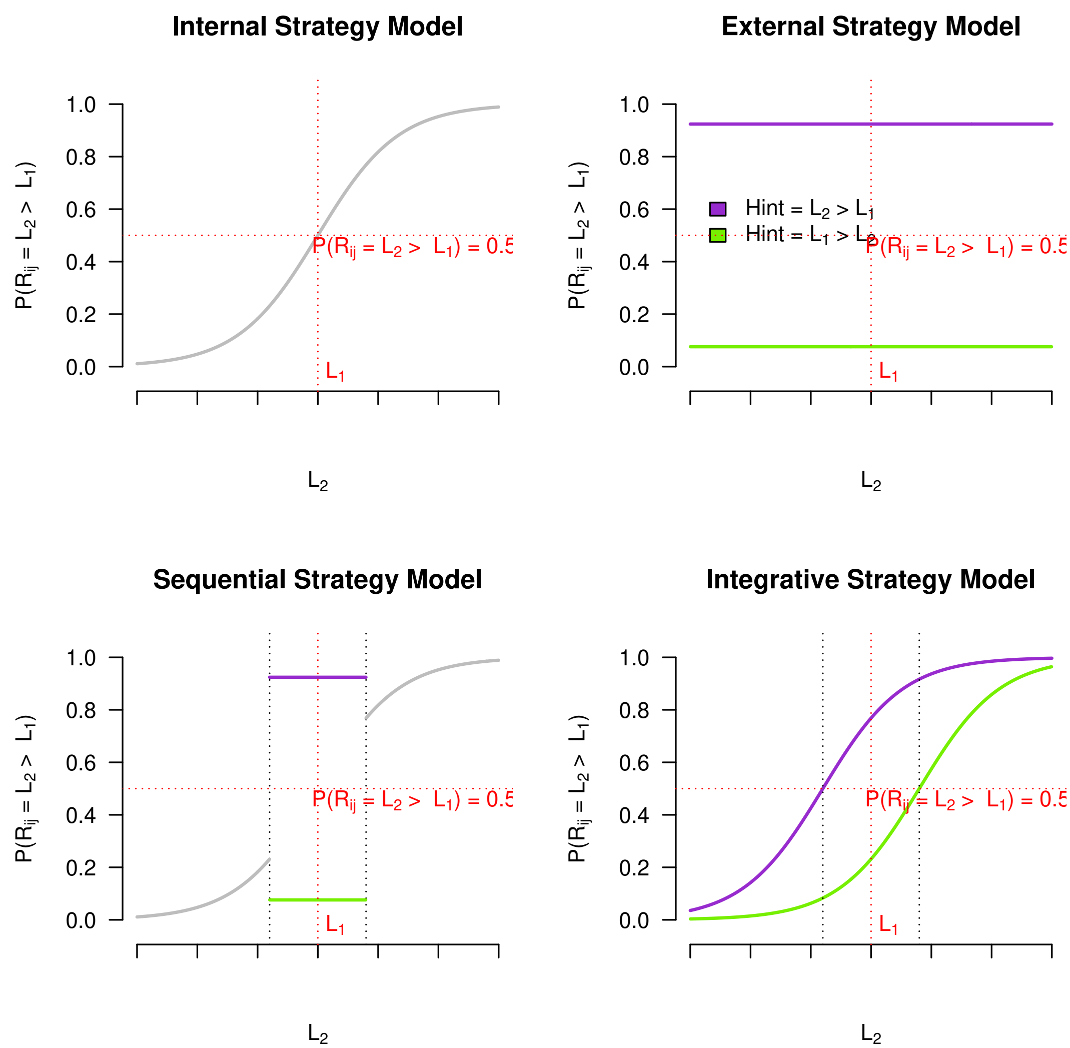


Figure 3: Illustration of the four models representing decision strategies of using internal or external information. The x-axis represents all possible values for the varying stimulus ($L_2$), the red vertical line indicating when $L_2 = L_1$. The y-axis represents the probability of responding "$L_2 > L_1$". The purple and green lines indicate the probability of responding "$L_2 > L_1$" when the hint (i.e., external information) pointed towards the correct response being "$L_2 > L_1$" and "$L_2 < L_1$", respectively. A) The internal strategy model: responses are solely determined by internal information. The grey line denotes the probability of responding "$L_2 > L_1$" unaffected by external information. Parameter $b_{int}$ determines the slope of the line. B) The external strategy model: responses are solely determined by external information. Parameter $b_{ext}$ determines the distance from the center of the y-axis for both the purple and green line. C) The sequential strategy model: when the stimuli are similar (i.e., close to the red line) responses are determined by external information, whereas when stimuli are dissimilar (i.e., far from the red line) responses are determined by internal information. Parameter $b_{int}$ determines the slope of the grey line; parameter $b_{ext}$ determines the distance from the center of the y-axis for both the purple and green line. D) The integrative strategy model: responses are determined by internal and external information simultaneously. Parameters $b_{int}$ and $b_{ext}$ determine the slope of, and distance between the purple and green line, respectively.

Note that decision making as predicted by the external model is not a function of the difference between $L_1$ and $L_2$. Instead, it implies a single choice probability for adherence to the hint quantified as the inverse logit of parameter $b_{ext}$. That is, a probability is estimated for each individual measuring their probability of responding in accordance with the hint for all items, regardless of whether $L_1$ or $L_2$ is longer.

**The Sequential Strategy Model.** According to the sequential model individuals make easy decisions based on internal information, while relying on external information when decisions are deemed too difficult, see Figure 3, lower left, and Equation 3.

$$P\left(R_{(ij)} = [L_{2(j)} > L_{1(j)}]\right) = \begin{cases} \frac{1}{1+e^{-(b_{int(i)} \times L_{\Delta(j)}}} & for\ z_{(i)} \leq L_{\Delta(j)} \leq -z_{(i)} \\ \frac{1}{1+e^{-(b_{ext(i)} \times\ hint_{(j)})}} & elsewhere \end{cases} . \quad (3)$$

In this logistic regression, the probability to respond "$L_2 > L_1$" is predicted by either $S_\Delta$ or $hint_{(j)}$. Parameters $b_{int}$ and $b_{ext}$ have the same interpretation as before. Strategy parameter $z_{(i)}$ is new. It describes the range of $S_\Delta$ in which participant $i$ considers items too difficult — the difference between stimuli is deemed too small — to rely on internal information, thus the participant relies on external information instead. Parameter $z$ can only assume positive values. If $z = 0$, the sequential model reduces to the internal model. The interval described by parameter $z$ being symmetrical dictates that only the absolute difference between $L_1$ and $L_2$ influences difficulty, regardless of $L_1$ or $L_2$ being longer. This is justified in the current task due to the balanced left-right presentation of $L_1$ and $L_1$. If $z = \infty$, it takes the form of the external model.

**The Integrative Strategy Model.** The integrative model predicts that individuals base all decisions on internal and external information simultaneously, rather than sequentially, see Figure 3, lower right, and Equation 4.

$$P\left(R_{(ij)} = [L_{2(j)} > L_{1(j)}]\right) = \frac{1}{1 + e^{-(b_{int(i)} \times L_{\Delta(j)} + b_{ext(i)} \times\ hint_{(j)})}}. \quad (4)$$

In this logistic regression, parameters $b_{int}$ and $b_{ext}$ have the same interpretation as before. If $b_{ext} = 0$, this model reduces to the internal model; if $b_{int} = 0$, it reduces to the external model.

**Guessing and Bias Models** Preliminary inspection of the data indicated that some individuals had merely guessed or gave strongly biased responses. To account for these individuals, three additional models were added to the analysis. According to the guessing model, responses were given at random. Thus, the probability of responding "$L_2 > L_1$" was drawn from a uniform distribution ranging from .45 to .55. According to the $L_1$ bias model and the $L_2$ bias model, responses were strongly biased towards either "$L_2 > L_1$" or "$L_2 < L_1$", respectively. In both these models, the probability of giving a bias-consistent response on any item was drawn from a uniform distribution ranging from .9 to 1.

### 2.3.2 Strategy Assignment Analysis

A Bayesian hierarchical mixture model analysis was used to assign strategies and estimate the corresponding strategy parameters on an individual level (Lee, 2011; Lee & Wagenmakers, 2013; Lodewyckx et al., 2011). The hierarchical mixture aspect of the analysis improves parameter estimation, and the hierarchical part specifically lends robustness against outliers (Piray, Dezfouli, Heskes, Frank & Daw, 2019).

We collected 50,000 samples, with a 10,000 burn-in sample to reduce the influence of parameter starting values, and thinning by factor 10 to reduce autocorrelation (Lee & Wagenmakers, 2013). Each of the 7 chains started with all participants assigned to a different model. Convergence of sampling chains was determined using Gelman-Rubin's Convergence Diagnostic, $\widehat{R}$, which compares between- and within-chain variability (Gelman & Rubin, 1992, but see: Vats & Knudson, 2018). $\widehat{R} < 1.1$ indicates successful convergence. $\widehat{R}$ was calculated for both individual- and group-level parameters. Unsuccessful convergence was followed up by manual inspection of traceplots for potential causes (e.g., too few samples, high autocorrelation) for the analysis to be rerun with the appropriate changes (e.g., more samples, more thinning).

Consistent with previous studies on strategy use in different domains, we assumed individuals to use the same strategy throughout the task (Heck et al., 2017; Hilbig & Moshagen, 2014; Lee, 2016; Steingroever et al., 2019). The strategy with the highest posterior probability of assignment was taken to underlie an individual's decision making. Bayes factors (BFs) then quantified the evidence for assigning this strategy as opposed to other strategies, both per individual and per age group. BFs were estimated using the product space method (Carlin & Chib, 1995; Lodewyckx et al., 2011) and interpreted following the guidelines by Jeffreys (1961; see also: Lee & Wagenmakers, 2013).

Strategy parameters were estimated simultaneously with strategy assignment. There were two types of parameters: group parameters and individual parameters. Group parameters describe characteristics of the group of participants assigned to a certain strategy model. Individual parameters describe characteristics of each individual assigned to a strategy model. The group parameters determined the distributions from which individual parameters were drawn (Lee & Wagenmakers, 2013). Parameters were examined on their median and 95% highest-density credibility interval (from now on: 95*CI*).

The strategy assignment analysis proved capable of estimating individual and developmental differences in strategy use as well as strategy parameters in the pilot study. Details on the analysis, including priors, can be found in Supplement B. All analyses were implemented in JAGS (Plummer, March 2003) via Rstudio (RStudio Team, 2018), through the R2Jags-package (see: https://cran.r-project.org/web/packages/R2jags/R2jags.pdf). Code can be found on the Open Science Framework https://osf.io/pe8jw/?view_only=4c3e221a699f475280b28f361206bcd5).

#### 2.3.3 Age Effects Analysis

Following decision strategy assignment and parameter estimation, the effects of age on strategy use and strategy parameters were examined. We expected an age-related increase in sequential or integrative strategy use. To test this, we performed two Bayesian logistic regressions with age predicting the posterior probability of sequential and integrative strategy assignment, respectively, versus that of all other strategies combined (Kruschke, 2014).

We explored the effects of age on strategy parameters using three Bayesian linear regressions investigating whether age predicted individual strategy parameters $b_{int}$, $b_{ext}$, and $z$. For each parameter, we included only the estimates of individuals assigned a strategy model that incorporates the respective parameter: $b_{int}$ was included only for the internal, sequential, and integrative models, $b_{ext}$ was included only for the external, sequential, and integrative models, and $z$ was included only for the sequential model. We tested the main effect of age on strategy parameters, not considering interactions with strategy. That is, how (for example) the ability to make decisions based on internal information changes with age is examined by looking at an overall change in parameter $b_{int}$, regardless of the which strategy incorporating $b_{int}$ people used.

Age-effects parameters were interpreted using the Savage-Dickey ratio density test[2] (Wagenmakers et al., 2010), and the median and 95*CI* of the posterior.

# 3 Results

## 3.1 Descriptive Statistics

Twenty participants were omitted due to missing responses on >10% of items. This resulted in a sample of 305 participants between the ages of 9 and 14 ($M_{age}$ = 11.6, $\sigma$ = 1.5), of which 142 were males. Demographic information is given in Table 1A-B.

A Bayesian logistic regression indicated no dependency between age in years (continuous) and sex (nominal), $BF_{b_{age}=0}$ = 11.7 ($b_{age}$ = .038, 95% CI [–.110;.183]).

Accuracy across age is depicted in Figure 4. A linear regression ($N$ = 305) provided insufficient evidence to support or refute claims of age (continuous, standardized) predicting accuracy, $BF_{b_{age}=0}$ = 2.2 ($b_{age}$ = .008, 95% CI[.002;.014]).

Pairwise comparison of strategy models on decision accuracy per age indicated that guessing and bias strategies were generally less accurate than the strategies of interest, though some comparisons yielded inconclusive results. The strategies of interest did not differ in accuracy. Details are found in Supplement H.4.2.

[2]Bayes factors > 3 indicate evidence in favor of the null-hypothesis — i.e., no difference/age effect. Bayes factors < .3 indicate evidence in favor of the alternative hypothesis — i.e., a difference/an age effect, the direction of which is to be determined by means of the median and 95% CI of the parameter's posterior distribution. A finding of 1/3 < BF < 3 indicates "anecdotal evidence" or evidence "barely worth mentioning" (Kass & Raftery, 1995; Jeffreys, 1961; Lee & Wagenmakers, 2013), which we thus interpret as insufficient evidence for either hypothesis — i.e., an inconclusive finding.

Table 1: A. Observed age and sex ($N$ = 305).

| Age in years | 9 | 10 | 11 | 12 | 13 | 14 | Total |
|---|---|---|---|---|---|---|---|
| $N$ | 34 | 54 | 47 | 64 | 74 | 32 | 305 |
| $\%_{male}$[a] | 47.1 | 54.7 | 42.6 | 46.8 | 44.6 | 48.4 | 46.6 |

B. Observed Education level and Sex (N=305)[b].

| Education Level | Primary | Secondary | | | Total |
|---|---|---|---|---|---|
| | | low | middle | high | |
| $N$ | 156 | 54 | 52 | 43 | 305 |
| $\%_{male}$ | 48.1 | 57.4 | 32.7 | 44.2 | 46.6 |

[a] Four participants did not provide information about their sex.

[b] Four participants did not provide information about their sex. High school education in the Netherlands is subdivided into three levels; preparatory vocational secondary education (here: "low"), senior general secondary education (here: "middle"), or university preparatory education (here: "high").

## 3.2 Main Results

Of group and individual parameters, 100% converged successfully as based on the $\widehat{R}$, as well as inspection of trace plots (details in Supplement C). Supplement E shows the predicted response probabilities alongside the observed responses per participant, as well as the percentage of correctly predicted responses per participant.

Individual posterior probabilities of strategy assignment, as well as resulting strategy model assignment overall and per age, are shown in Figure 5.

Individual BFs ranged from moderate to extreme evidence in favor of the individually assigned strategy (details in Supplement D). At ages 9 through 13, moderate evidence supported assignment of the internal relative to other strategy models (BFs ≥ 3.5). At age 14, integrative and internal strategy assignment were approximately equally likely (BF = 1.3). An overview of strategy model comparisons is found in Supplement D.[3]

A logistic regression provided strong evidence that age did not predict the probability of integrative versus other strategy assignment, $BF_{b_{age}=0} = 15.7$, ($b_{age} = -.022$, 95% CI[–.143; .093]). The same was observed for the probability of sequential versus other strategy assignment, $BF_{b_{age}=0} = 15.2$ ($b_{age} = .010$, 95% CI[–.119; .137]). We conclude that neither

[3]These Bayes factors quantify the proportion of evidence in favor of assignment of the strategy model relative to the strategy model(s) to which it is compared. For example, when comparing the internal to the integrative strategy model, BF=4 indicates that assignment of the former is four times more likely (Lee & Wagenmakers, 2013). Contrary to the BFs considered earlier, here 1/3 < BF < 3 does not indicate insufficient evidence in favor of the null-hypothesis or the alternative hypothesis — i.e., an inconclusive finding — but rather insufficient evidence in favor of either of the compared strategy model(s) being more likely — i.e., we conclude that the compared strategy models were equally likely.

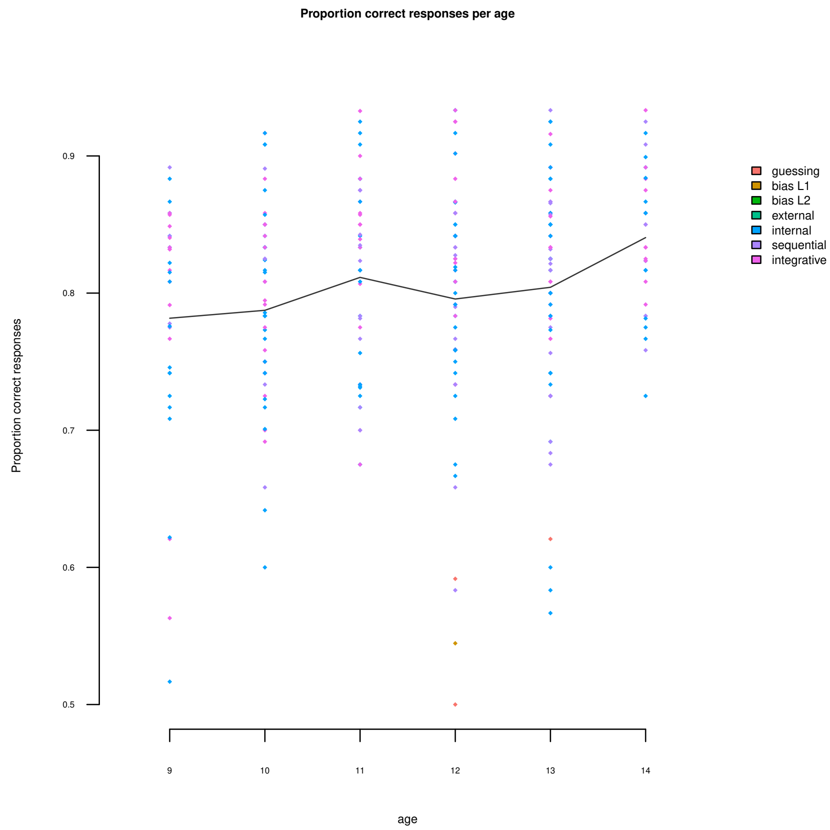


FIGURE 4: The distribution of the proportion of correct responses for 9- to 14-year-olds (left to right).

sequential nor integrative strategy use increased with age.

Three linear regressions were performed to see if age predicted strategy parameters $b_{int(i)}$, $b_{ext(i)}$, and $z_{(i)}$, including only participants assigned a model containing the corresponding parameter ($N_{b_{int}}$=300, $N_{b_{ext}}$ = 158, $N_z$ = 64). Moderate evidence indicated that neither $b_{ext}$ or $z$ changed with age, $\text{BF}_{b_{age\,ext}=0}$ = 15.5 ($b_{age\,ext}$=.011, 95% CI[–.001;.023]); $\text{BF}_{b_{age\,z}=0}$ = 848.9 ($b_{age_z}$=.000, 95% CI[–.001; .001]). Findings concerning an age-related change in $b_{int}$ were inconclusive, $\text{BF}_{b_{age_{int}}=0=2.7}$ ($b_{age_{int}}$ = .050, 95% CI[–.001;.100]).

A downside of using Bayes factors for hypothesis testing is that they are dependent on the chosen priors (Etz et al., 201; Wagenmakers et al, 2010). This proves an issue for this particular study as the priors are hard to substantiate given the absence of pre-existing theory or previous empirical work on the matter. To test the robustness of our conclusions, we give a detailed overview of findings using two different sets of priors in Supplement H. The prior sets produced similar findings.

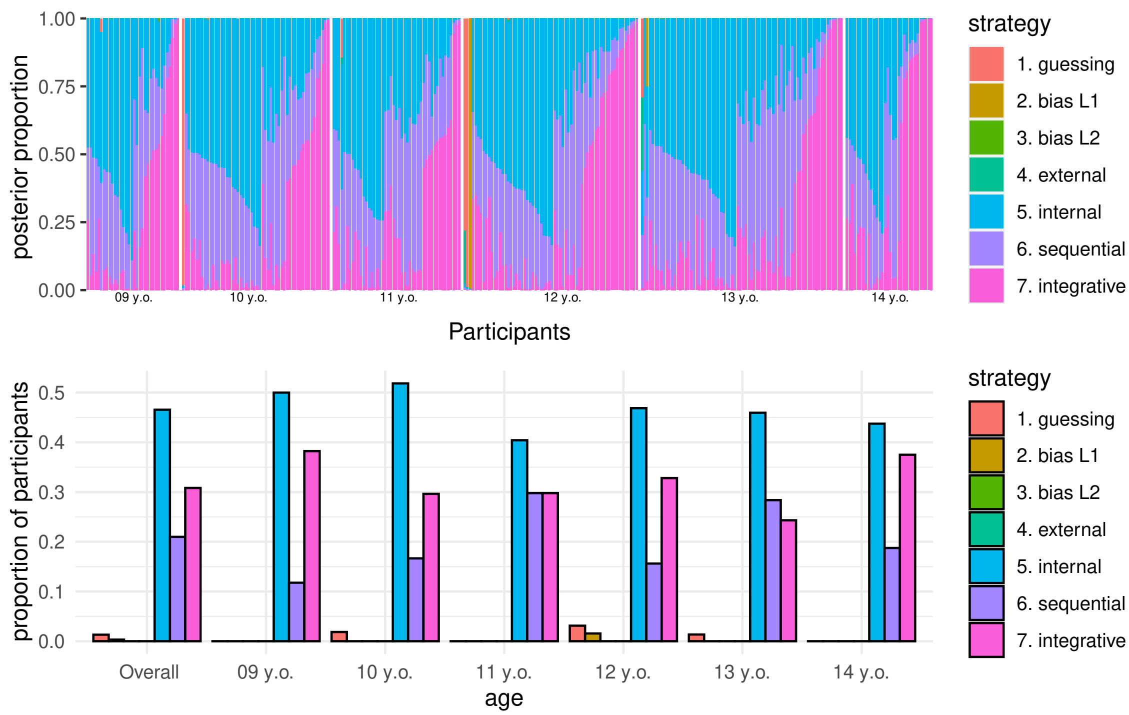


Figure 5: Strategy assignment. Upper panel: posterior probability for different strategy model assignments per participant. The x-axis denotes participants across age groups, with each bar representing one participant. Each color within a bar represents a different strategy model, stacked in legend order. The y-axis denotes the posterior probability of different strategy model assignments across samples. The dominant color within a bar denotes which strategy model was assigned to the corresponding participant. Bottom panel: bar plot of strategy model assignment overall (left), and per age group (right). In each panel, each bar representing a different strategy model. The y-axis denotes the proportion of participants per age group assigned to a particular strategy.

# 4 General Discussion

This study examined individual and age differences in decision making strategies of using information obtained individually — i.e., internal information — and information provided by external sources — i.e., external information — in 9 to 14-year-olds. Several models were compared in which decisions were based on different types of information: the internal strategy that is reliant on only internal information, the external strategy that is reliant on only external information, the sequential strategy that relies on external information only if internal information is deemed inadequate, and the integrative strategy that relies on the integration of internal and external information.

As expected, individual differences in decision strategy use were observed. The internal and integrative strategy were most prominent, followed by the sequential strategy. The external strategy was rare. Contrary to expectations, no age-related increase in sequential or integrative strategy use was observed. Similarly, no age-related changes were observed in the extent to which external information influenced decision-making behavior. Findings regarding age-related changes in the effects of internal information on decision making as well as decision accuracy were inconclusive. We conclude that individual differences in strategy use exist — the most prominent strategies being the internal and integrative strategy — but that neither sequential nor integrative strategy use changes systematically with age in 9 to 14-year-olds.

Absence of the expected increase in strategies reliant on both internal and external information in the decision-making process in the 9–14 age range appears contradictory to earlier findings that adolescence is a period marked by heightened influence of external information (Bednar & Fisher, 2003; Blakemore & Robbins, 2012; Dekkers et al., 2018; Gardner & Steinberg, 2005; Steinberg, 2008; Sumter et al., 2009; Zwane et al., 2004). A potential explanation is that the anticipated strategy change occurs in mid- to late adolescence, in the 14–18 age range.

Despite our expectations concerning age-related strategy changes not being met, most results both concur with, and add to previous findings. Firstly, we replicated the phenomenon that most people are influenced by external information (Asch, 1956 ; De Martino et al., 2017; Einav, 2014; Heck et al., 2017; Hilbig & Moshagen, 2014; Walker & Andrade, 1996; Morgan et al., 2012, 2015). This contributes to a body of work showing that external information from a single, non-expert source may also affect decision making (Hertz & Wiese, 2016, 2018). Secondly, infrequent use of the external and sequential strategy across ages suggests an inherent tendency not to abandon internal for external information entirely, consistent with a previously observed priority given to internal information (Puskaric et al., 2017; Schrah et al., 2006; Toelch et al., 2014). Thirdly, observation of the sequential strategy — a newly proposed mechanism of relying on both internal and external information in decision making distinct from integration — suggests that this strategy should be included in future research. Strategies of sequential information consideration are established in other decision-making domains (Dekkers et al., 2020; Jansen et al., 2012; Svenson, 1979; Van Duijvenvoorde et al., 2016; Zadelaar et al., 2020).

Research applying a similar design to adults reported strong individual differences in strategy use as well, with the integrative strategy being most common (Molleman et al., 2020). This suggests that individual strategy variability as found in the current study carries over into adulthood. Moreover, the integrative strategy being dominant in adulthood suggests an age-related increase in the use of this strategy between late-childhood and adulthood, with current findings suggesting this to occur *after* the age of 14. Integrative strategies of internal and external information use being more dominant in adults than children matches some findings from reinforcement learning literature (Betsch et al., 2018; Mata et al., 2011) but contradicts others (Klayman, 1985; Mata, von Helversen & Rieskamp, 2010). Something shared by all of these studies is the observed influence of task characteristics — e.g., type of decision making, use of external information, agreement between internal and external information — on strategy use, which may explain these seemingly conflicting findings. Along with previous authors, we thus advocate caution when generalizing current findings to novel settings.

When generalizing current findings to real-life decision making, one must take into account that the decision task involved identifying an objectively correct answer (i.e., the longest line) rather than making a moral, proper, or preference judgement. When deciding what the objectively correct answer should be, the role of external information tends to be predominantly informational: driven by a need for additional knowledge or insight. When deciding on a moral, proper, or preference judgement, the role of external information is predominantly normative: driven by a need to conform to and connect with others (Kaplan & Miller, 1987). As research suggests that people behave differently in reaction to informational versus normative influences (Lord et al., 2001; Mangleburg et al., 2004; Mascarenhas & Higby, 1993), we caution against generalizing the presented developmental trajectory to decision making where external information plays a predominantly normative role, such as deciding whether or not to smoke when peers do. In fact, a potential explanation that the expected age-related increase in susceptibility to external information was not found is that this may occur mainly in decision making where external information exerts a predominantly normative influence.

Related to the previous point, the external information source in the current task was a stranger. While literature shows that even unknown peers can affect children's and adolescents' decision making (Dekkers et al., 2020; Wagenmaker et al., 2020), external information sources with whom the decision maker has a closer social connection, such as friends or family members as opposed to strangers, tend to have a stronger influence (Kim et al., 2017; Magee & Smith, 2013; Sun et al., 2017). However, this effect of social connection appears absent when the decision maker's external information seeking is predominantly informational — at least when the decision making happens anonymously (Herzt, 2018). This suggests that current findings translate to decisions where the external information source is someone familiar or even close to the decision maker, provided that external information fulfills a predominantly informational role, like when cheating off of someone on an exam.

Prior research suggests that trust in external information depends on its frequency as well as its accuracy (Lee & Dry, 2006). Specifically, highly accurate but rarely provided advice was trusted less than more frequent but less accurate advice. One explanation is that, in the former situation, the external information source is perceived as cautious due to poor ability (Sniezek & Van Swol, 2001; Soll & Larrick, 2009). Thus, perceptions of the external information source through experience may impact the use of external information. Noteworthy is that such perceptions may change during the task. For example, coming across obviously incorrect external information may logically reduce trustworthiness of the source (Diaconescu et al., 2014; Pasquini et al., 2007; Vélez & Gweon, 2019), consequently reducing reliance on external information in subsequent items. While beyond the scope of the current study, including perceived accuracy of external information into the model as a parameter that varies across participants and trials may improve both individual strategy assignment and parameter estimation (Diaconescu et al., 2014). It may also help identify individuals who update accuracy perceptions in the face of external information aberrantly often, potentially signaling a heightened vulnerability to suboptimal or even harmful influences. Perceived accuracy of external information may either be estimated as a model parameter — e.g., as predicted by true external information accuracy and frequency — but can also be measured — e.g., by asking participants for an accuracy or trustworthiness judgement on the external information source.

This study had several assets. Firstly, the large sample size aided in forming a representative overview of strategy use both across ages 9 to 14, and per year of age. Including children and adolescents from all education levels further increased representativeness of strategy use in this age range of interest.

Secondly, the investigation of both strategy use and the effects of internal and external information was made possible by Bayesian hierarchical mixture analysis, which estimates both mechanisms simultaneously. This prevents misinterpretation of one mechanism for another. Another advantage of this method is that strategy assignment and parameter estimation are based on a single task, rather than one task including external information and one task excluding external information as is often done (Molleman et al, 2019; Morgan et al., 2012, 2015). This negates the necessity of controlling for learning effects and reduces administration duration, likely reducing the effects of fatigue and motivational decline on performance, which is especially important in developmental samples. Thus, we see potential in further application of this analysis in the study of processes underlying individual differences and age-related changes in decision behavior in the presence of both internal and external information.

A potential limitation of this study is that parameter priors could not be based on previous research as, to our knowledge, there currently exists no research to model all decision strategies of interest in this context. Stricter priors in the strategy assignment analysis would cause more pronounced distinctions between strategy models, resulting in more certain strategy assignment (Lee & Wagenmakers, 2013). For example, if the sequential strategy requires that external information, when used, must inform at least 99% of decisions, chances that this strategy is wrongfully assigned to individuals actually using the internal strategy are slim. However, priors this strict may reflect such unrealistic demands of human behavior that the corresponding strategy is never assigned. Current priors were chosen based on conceptual considerations and assumptions of the psychological variables of interest — e.g., assuming that people are unlikely to respond contrary to internal information — an advisable approach in Bayesian literature (Lee & Vanpaemel, 2018; for opposing viewpoints see Lemoine, 2019). Yet, a simulation study could determine empirically which prior distributions and constraints strike an optimal balance between strategy assignment sensitivity and specificity.

A second limitation of the current study was its two-step analytical method wherein first strategy use was estimated and only then age effects were considered. As a consequence, the uncertainty in strategy inference is not carried over into the age analysis, which may have therefore under- or overestimated age effects. However, a one-step method required expanding the current hierarchical mixture model to a hierarchical mixture *path* model — one where age first predicts strategy use which, in turn, predicts decision-making behavior — which proved beyond the scope of the current study. However, we encourage the development and testing of such expansions in future research.

A third potential limitation is that the class-wise format of test administration at schools implemented a time limit, which can impact decision strategy use. That is, under time pressure individuals who would otherwise use the integrative strategy may resort to the less complex internal strategy to reduce cognitive strain (Kwak et al., 2015; Payne, 1976; Payne et al., 1988). Future research may address this by comparing strategy use within individuals across conditions of varying time constraints. As findings may be susceptible to individual differences such as differences in experienced time pressure, the current hierarchical mixture method would be highly suitable for this purpose.

### 4.1 Conclusions

In perceptual decision making in 9 to 14-year-olds, individual differences but no age-related changes were observed in the use of strategies describing how individually obtained information or information provided by others influence decision making. This suggests the need to take into account qualitative between-individual differences in the way both types of information are used in this age range, both in research and practical situations. This specifically pertains to decision making in which information provided by strangers in sought out by the decision maker with the aim to gain additional insight or knowledge, which is prevalent in an increasingly virtual/online society (Wang et al., 2012; Xiang, 2019; Zhao et al., 2018). While these findings ought to be replicated in more ecologically valid studies, they provide a stepping stone in understanding the mechanisms of decision making in the presence of information provided by external sources.

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