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Adapt or Exchange: Making changes within or between contexts in a modular plant scenario

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Most psychological studies on the balance between stability and flexibility in decision making restrict their experiments to simplistic scenarios. These restrictions likely affect the decision process, and it is unclear which findings can be transferred to more naturalistic decision contexts. Therefore, the present study used a scenario that is inspired by the problem structure found in a particular domain: Adapt/Exchange decisions in modular chemical plants. In this setting, we investigated two findings from the decision making literature: whether participants refrain from a thorough comparison of options and whether they perseverate on previous choices. Forty-eight participants made Adapt/Exchange decisions and subsequently implemented them in specific parameter settings. Between four blocks of trials with sequential trial orders, we varied sequence direction (i.e., whether the costs of Adapt gradually increased or decreased) and sequence type (i.e., whether gradual changes were only present in the option ratio or also in absolute costs). We analyzed the percentage of Exchange choices, option switches, decision times, and parameter settings. The results suggest that instead of comparing options, participants used a satisficing strategy, checking whether Adapt was good enough and only considering Exchange if it was not. The direction of sequence effects was opposite to the predicted choice perseveration: In sequences initially favoring Adapt, participants started exploring the Exchange option early on, while in sequences initially demanding Exchange, they preferred Adapt as soon as it became possible. The results raise questions about the application of psychological theories to complex decisions between qualitatively different options.

Keywords: decision making, goal conflicts, stability-flexibility balance, heuristics, sequence effects, modular plants, process industries

When faced with problems, people often have to decide whether they should only make minor adaptations to the status quo or fundamentally change the situation. Such decisions are omnipresent in real-life decision contexts: Should people adjust the recipe that resulted in a mediocre meal last time or choose a recipe that is easier to cook? Should they fix their broken bike or buy a new one? Should they invest in a troubled marriage or start dating their charming next-door neighbor? Such decisions are challenging and it would be interesting to know how people deal with them. For instance, how long do they stick with mere adaptations to the status quo? How thoroughly do they consider more fundamental changes? The decision making literature does not provide direct insights into the level on which people prefer to make changes. In the following sections, we introduce the balance between stability and flexibility from a theoretical perspective, and then present modular plants as a real-life context in which decisions about the level of changes are required. We then compare the situation in modular plants with tasks typically studied in psychology labs. Based on this analysis, it turns out that it is far from clear whether findings from the decision making literature will hold in this scenario. To investigate this issue, we derive two research questions for the present study.

The stability-flexibility balance in decision making

Adaptive action control requires people to solve the dilemma of balancing stability and flexibility (Goschke, 2013; Hommel, 2015). On the one hand, they can stay with their current options, apply quick fixes, and (re-)use solutions that are good enough. On the other hand, they can select the options most suitable for a specific situation, adapt their strategies to current requirements, and apply solutions that might be best in the long run. The optimal balance between stability and flexibility is determined by current goals and characteristics of the task context (Chrysikou, Weber, & Thompson-Schill, 2014). Such characteristics include the presence of conflict (Botvinick, Braver, Carter, Barch, & Cohen, 2001; Chatterjee & Heath, 1996; Tversky & Shafir, 1992), the volatility of the environment (Jiang, Heller, & Egner, 2014; Knox, Otto, Stone, & Love, 2012), or the complexity of decision contexts (Timmermans, 1993). Such complexity can even lead people to refrain from making a decision altogether (Dhar, 1996; Iyengar & Lepper, 2000; Tversky & Shafir, 1992). Instead, they go with defaults (Johnson & Goldstein, 2003; Pichert & Katsikopoulos, 2008) or leave the situation as it is (*status quo bias*; gal, 2006; Ritov & Baron, 1992; Samuelson & Zeckhauser, 1988).

These and similar results have greatly enhanced our understanding of basic decision processes. However, most psychological studies on the stability-flexibility balance use paradigms that differ from real-world decision contexts in particular ways. In the following sections, we first introduce an example of a real-world decision context in which

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balancing stability and flexibility is crucial, and then explain the main differences from most psychological studies.

Modular plants

In the process industries, raw materials are transformed into products in chemical and physical processes (Dennis & Meredith, 2000; Fransoo & Rutten, 1994; Müller & Oehm, 2019). To this end, traditional process plants combine a limited set of general purpose equipment (e.g., reactors, pumps, valves), and tightly coupled, distributed processes are coordinated via plant-wide control strategies (Urbas, 2012). In contrast, modular plants are designed like Lego: Highly automated, almost autonomous processing units can flexibly be combined according to current requirements (Urbas, Doherr, Krause, & Obst, 2012). This provides decision makers with two qualitatively different options for achieving production goals: They can either adapt process parameters (e.g., increase temperature or pressure) or change the physical module setup (e.g., use a bigger reactor module). Thus, they need to decide whether to fix a problem in the current physical context or change the context as such. These options, Adapt or Exchange, have different costs and benefits. For instance, while simply adapting parameters saves time and effort, exchanging modules might be much more efficient as production can proceed with the equipment most suitable for achieving current production goals. In consequence, the work in modular plants is characterized by a need to deal with goal conflicts — decision makers have to balance requirements for process efficiency, product quality, plant safety, and effort reduction, to name but a few. Therefore, operating a modular plant requires a flexible, situation-specific adaptation of options, decision strategies, and meta-control policies (for a detailed discussion of decision requirements in modular plants see Müller & Urbas, 2017).

Decisions in modular plants versus psychology experiments

In some ways, Adapt/Exchange decisions in modular plants confront decision makers with challenges of balancing stability and flexibility that have been addressed in many previous studies on decision making: How to compare and select options? What attributes to consider for that? How long to stick with the current option and when to change? In other ways, modular plants represent a decision context that is quite different from most psychological studies.

First, adapt/exchange decisions require people to decide whether they want to stay within the current context (i.e., physical setup) and only make small modifications to it, or whether they want to make more radical changes by switching the context as such. This can be considered as moving up a step in the abstraction hierarchy: not only asking how to change the specific realisation of a particular solution principle but asking whether the principle as such is appropriate. While there is some work on hierarchical task switching (Kleinsorge, Heuer, & Schmidtke, 2004) and on the question whether task switching phenomena change when global situation features change (Mayr & Bryck, 2005), to our knowledge there are no studies investigating how people decide between local and global changes.

Second, Adapt and Exchange represent qualitatively different options. In typical multi-attribute decision making experiments, two or more options differ in their values on a set of shared attributes. In contrast, Adapt and Exchange have attributes with different levels of sharedness: Some attributes are shared and only differ quantitatively (e.g., parameter adjustments required to achieve acceptable product quality). Some attributes apply to both options in principle, but are negligible for one of them (e.g., risk of not achieving production goals: considerable for Adapt but negligible for Exchange as this is the very purpose of exchanging). Finally, some attributes only apply to one option (e.g., effort of physically reconfiguring the plant, risk of causing damage during this reconfiguration). Thus, the two options are characterized by partly non-overlapping attributes.

Third, Adapt and Exchange represent different means to achieve a specific goal. In the decision making literature, people are usually free to choose between options in whatever way they want. For instance, in delay discounting paradigms they choose between a sooner-smaller and a larger-later reward (Berns, Laibson, & Loewenstein, 2007; Frederick, Loewenstein, & O'Donoghue, 2002), and they can weight the values and costs according to their personal preferences. In contrast, for Adapt/Exchange decisions the goal state is often fixed (e.g., an urgent customer order requires producing a certain amount, or the foam risk must be kept below some threshold). These constraints are outside the decision maker's control, and his or her only choice is how to achieve them. However, Adapt and Exchange can differ in their potential to satisfy certain criteria for solution quality (e.g., disturb the process as little as possible). This results in an optimization problem. In principle, such problems are objectively solvable by means of mathematical optimization procedures. However, this presupposes that all priorities are known and can be quantified. For instance, in order to weight production effort against the risk of harming the product, all context factors influencing the priorities would have to be considered. In consequence, it is unrealistic to assume that Adapt/Exchange decisions can be fully automated.

Fourth, for Adapt/Exchange decisions, simply choosing an option does not determine the outcome. In the psychological literature, people typically make simple choices between two or more options and with that they are done. That is, their decision is the only and final act, while there is no need to consider how to implement it. In other words, most psychology studies only ask what people choose but not how this choice shapes and constrains their actions directed towards a desired goal state. Instead, Adapt/Exchange decisions need to be implemented in the form of specific parameter settings. Hence, the quality of a solution does not only depend on people's choice but also on how they put it into practice. For instance, if you exchange an old module for a new module but then do not make use of its capacity, the choice is not beneficial. Accordingly, the available options only define the frameworks in which specific action selection is needed to achieve particular goals.

Finally, a number of general factors differentiate Adapt/Exchange decisions from the decisions typically studied in psychological experiments. For instance, in most studies decisions are made in a rapid succession of many trials, so there is no chance to thoroughly contemplate the consequences of different options. Also, studies often use decision contexts with low complexity, and interactions between different variables are rarely considered. In contrast, a research tradition that explicitly considers these factors is the literature on complex problem solving (for an overview see Fischer, Greiff, & Funke, 2012). These studies typically use microworlds in which participants have to manipulate different variables in order to achieve desired outcomes. For instance, in *Tailorshop* (e.g., danner et al., 2011), participants run a business that produces and sells shirts by manipulating twelve of twenty-four interconnected variables (e.g., number or workers, expenses for advertising). An industrial simulation is *PowerPlant* (Wallach, 2017), where participants have to generate power and control steam pressure by manipulating fuel mass flow and the position of a turbine valve. Such simulations have resulted in a wealth of interesting findings, for instance on the strategies people use to solve complex problems, the transferability of complex problem solving skills, or the role of expertise and intelligence. However, they do not allow us to study how people balance stability and flexibility when making decisions in contexts like modular plants. First and foremost, these simulations do not allow participants to make changes to the system setup (e.g., module exchanges), and thus cannot answer how people choose between mere parameter adaptations and changes of the system structure (i.e., local and global changes). Second, they do not support the investigation of discrete choices (i.e., many similar decisions) while varying situational features that are expected to influence these choices. Instead, they provide one uniform scenario (microworld) in which participants can perform a variety of actions to affect the system state. Finally, they are intentionally kept abstract and do not aim to represent domain features like the ones discussed above.

Taken together, situations like the ones arising in Adapt/Exchange decisions have not been addressed sufficiently in the psychological literature. This is a serious shortcoming as the aforementioned structural characteristics of these decisions are by no means restricted to modular plants. Therefore, studying Adapt/Exchange decisions can provide valuable insights for our understanding of decision making in domains far beyond the process industries.

Psychological questions to study in modular plant scenarios

The present study asks how findings from the decision making literature on the stability-flexibility balance ~~will~~ play out in decision contexts with the structural features presented above. Therefore, we chose two exemplar questions and studied them in the domain of modular plants: whether people systematically compare options when making Adapt/Exchange decisions, and whether they perseverate on previous choices in sequential decision making.

Do people thoroughly compare options?

When people compare options, they can do so by using strategies that vary in their effort of information sampling and integration (Bettman, Johnson, Luce, & Payne, 1993; Payne, Bettman, & Johnson, 1988). On one end of the spectrum, people can engage in a thorough comparison of all available options on all of their attributes weighted by their respective relevance. However, ample research suggests that people often use simpler strategies or heuristics instead (Gigerenzer, Todd, & The ABC Research Group, 1999; Kahneman, Slovic, & Tversky, 1982). For instance, they might focus on the most important attribute and check which option performs best on it, or check options separately until one of them is good enough. Although the choice of strategies is highly dependent on context (Bettman et al., 1993; Gigerenzer et al., 1999; Payne et al., 1988), a general conclusion is that people often do not engage in a thorough, systematic comparison of all options. Why might this be different for decisions in modular plants? As stated above, these decisions are not merely a matter of preference but have to satisfy specific solution criteria. This might foster a thorough sampling and integration of information. On the other hand, decisions in modular plants are more complex than those in most psychology experiments. In consequence, heuristics such as satisficing (which are sometimes perceived to be a consequence of excessive task difficulty) could be expected.

Do people perseverate on previous choices?

A second question is how the decision history influences subsequent decisions. People often continue to choose the options they have chosen in the past (Alós-Ferrer, Hügelschäfer, & Li, 2016; Betsch, Haberstroh, & Höhle, 2002; Dutt & Gonzalez, 2012; Scherbaum, Dshemuchadse, Leiberg, & Goschke, 2013). Such bias in repeated choices has also been studied in dynamic decision making, where outcomes change over time (for an overview see Gonzalez, Fakhari, & Busemeyer, 2017). It was found that people adapt to changes in outcomes very slowly, so that it takes them quite some time to adjust their choices to new situational constraints (Brown & Steyvers, 2005). This is the case especially when an option has produced many good outcomes in the past (Rakow & Miler, 2009). How fast people adapt their choices to new situational constraints depends on the direction of change (Cheyette, Konstantinidis, Harman, & Gonzalez, 2016): They are slower when a previously inferior option improves in its outcomes than when it gets worse, because they do not choose it anymore and thus fail to notice the improvement.

Choice perseveration also occurs when people are fully informed about the outcomes of their decisions beforehand and thus do not have to infer the quality of options from experience. This has been shown in studies of delay discounting, where the options differ on two attributes (e.g., smaller-sooner vs. larger-later reward). In such tasks, choice perseveration manifests in sequence effects also known as *hysteresis* — systematic biases in the choice of options depending on the direction in which their attributes are changing (Scherbaum et al., 2016;Schoemann & Scherbaum, 2017; Senftleben, Schoemann, & Scherbaum, submitted; Senftleben et al., 2019). For instance, if participants start with trials in which a larger-later option is clearly preferable but then progressively gets worse, they continue choosing this option for longer and switch to the sooner-smaller option later than when they experience the opposite sequence direction, starting with trials in which the sooner-smaller option is preferable and then the larger-later option gets better. Modular plants are designed for frequent module exchanges. Therefore, subsequent Adapt/Exchange decisions have to be made and choice perseveration might be expected. However, due to the marked differences between Adapt/Exchange decisions and psychology experiments, it would be premature to take this for granted.

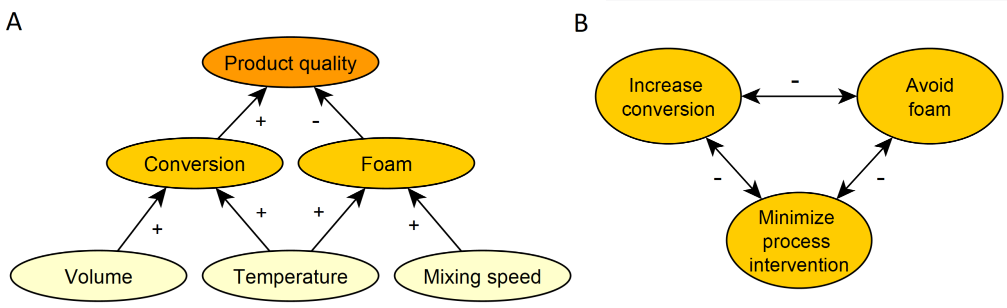

Figure 1. Constraints in the modular plant scenario. (A) Causal diagram representing the relations between process parameters and outcomes. (B) Goal conflicts affecting the selection of parameter adjustments.

Present study

To investigate decision processes in scenarios that share the problem structure of modular plants, we first had to develop a scenario that can be used for experimental studies in the lab. The decision task should contain the features of decisions in modular plants (see section *Decisions in modular plants versus psychology experiments*), while at the same time being simple enough to allow for controlled studies with student participants. To this end, a computer-based scenario was developed in which participants had to decide whether they wanted to adapt parameters in a currently used, small reactor module or exchange it for a module with a bigger reactor.

These decisions were made in the following decision context: Participants were responsible for enhancing the product quality in a chemical process, which depended on two factors (see Figure 1A): *conversion* (i.e., ratio of how much of the medium has reacted) and *foam* (i.e., a risk of destroying the product). Participants had to increase conversion while avoiding foam. At the same time, they had to minimize their degree of intervening in the process as each intervention constituted a risk. The specific actions available to them were adjustments of three process parameters (*volume, temperature, and mixing speed*). Conversion could be increased by increasing volume or temperature, while the risk for foam also increased when increasing temperature but could be reduced by reducing mixing speed. Note that temperature had a positive effect on product quality via conversion and a negative effect via foam. Thus, conflict resulted from the fact that in order to achieve the required conversion, participants had to increase volume and/or temperature, with the latter also increasing the foam risk and constituting an unwanted process intervention. To avoid foam, participants could manipulate mixing speed, but this increased their process intervention even more (see Figure 1B).

How these parameters could be adjusted depended on which reactor module was used: a small or a big one. Both modules had different but overlapping operating ranges (i.e., possible parameter settings), but these ranges were quite limited for the currently used small module and much higher for the bigger module that was available for exchange. Their relation to the causal process was as follows: When only adjusting parameters in the current small module (Adapt), volume could not be used to increase conversion as the reactor was almost full already. Therefore, participants had to rely on temperature and compensate its negative effects via mixing speed. When swapping the small module for the big one (Exchange), participants could increase volume, making it less necessary to adjust temperature and compensate its effects. Thus, while Exchange implied physical effort, it allowed for a safe achievement of conversion and minimization of process intervention.

Pilot study

We first conducted an explorative pilot study (Müller & Urbas, 2019) to gain a better understanding of how people act when faced with the problem context of modular plants. How do they spontaneously choose between Adapt and Exchange, and how do they adjust process parameters accordingly? What strategies do they use for information sampling? And finally, how much task difficulty can student participants handle? To address these questions, a rather unconstrained setting was used in which forty participants could freely navigate between different screens (e.g., plant diagrams, module characteristics, process relations) to sample different types of information. Distractor information was used to increase ecological validity. Between experimental scenarios, we varied whether the desired outcomes could be achieved via Adapt or whether Exchange was necessary. Two groups of participants received different types of visual support: One group could inspect graphical representations of the relations between all relevant process variables, represented as curves that depicted the impact of the adjustable parameters on conversion and foam. A second group received a set of eight cases (i.e., solution examples from previous problem solving episodes) that differed in the degree to which they represented suitable solutions.

The results reflected the complexity of the task setting: A first striking result was that participants were rather insensitive to differences between scenarios. Even when production goals could safely be achieved via Adapt, participants frequently chose Exchange. Even when the goals could only be achieved via Exchange, the rates of choosing Adapt and Exchange were comparable. Thus, participants' decisions did not mirror the objective requirements, indicating that the complexity of the experimental setting exceeded their capabilities. This conclusion was further supported by the finding that participants only met both outcome goals (i.e., achieve conversion and avoid foam) in 63% of the trials. Moreover, there were large interindividual differences. For instance, while some participants only used minimal process interventions, others made excessive parameter adjustments. While some participants frequently missed the required conversion, others failed to avoid foam. Also, participants differed in how much attention they dedicated to distractor information. In contrast, performance hardly depended on the experimental manip-

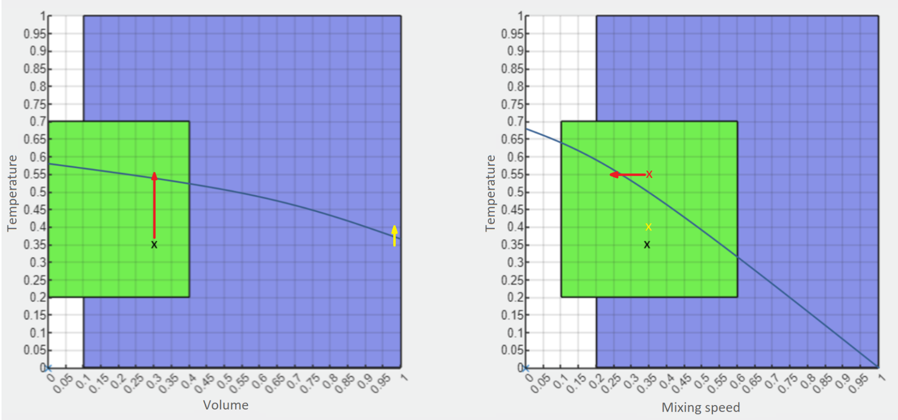

Figure 2. Relations between process parameters and outcomes, exemplar curves for one trial. Green and purple areas represent the parameter ranges of the small and big module, respectively, and the black crosses indicate the current parameter settings. The presented trial has an Adapt/Exchange ratio of 6:1 (note that volume is not included in the step number calculation and the picture). Thus, six steps are required for Adapt: four for temperature and two for mixing speed (see red arrows), while only one temperature step is required for Exchange (see yellow arrow).

ulation, namely whether participants were supported by process relations or cases. With cases, participants influenced the process less strongly, but the production outcomes did not differ. A full description of the methods and results of the pilot study is made available via the Open Science Framework: https://osf.io/5fcys/.

In conclusion, the pilot study provided interesting and helpful insights, but also emphasized that few participants were able to deal with the complex scenario. To put it harshly, one cfould say we were observing what people do when faced with excessive task difficulty, instead of studying informed decision making in modular plants. Accordingly, several effects seemed to drown in the large variance of individual strategies and capabilities. Still, the experiment provided us with a much clearer idea of how participants deal with modular plant scenarios, laying the foundations for planning more controlled, theoretically motivated, and yet domain-specific experiments to study decision making in modular plants. In terms of specific lessons learned, the following changes were made in the present study. First, the scenario was simplified (i.e., lower complexity of the causal process, standardized parameter ranges, omission of distractor information). Second, the graphical presentation of process relations curves was simplified to facilitate information integration. Third, in all but one trial per sequence, Adapt was a possible solution. Finally, the number of trials was increased from 6 to 40, which became possible as a consequence of the simplifications listed above.

Main study

The aim of the main study was to investigate whether Adapt/Exchange decisions rely on a thorough comparison of options and how they are affected by a sequential presentation of decision problems with changing constraints. To this end, we used a sequential manipulation in which the cost ratio of Adapt and Exchange (i.e., relative costs of the two options) changed across subsequent trials. Costs were operationalized as the process intervention required to achieve conversion and avoid foam, quantified in units of temperature and mixing speed change (henceforth called steps, see Figure 2). A 2 (*sequence type*: linear, mixed) × 2 (*direction*: ascending, descending) within-subjects design was used. An overview of definitions of the main concepts is provided in Table 1.

First, to study whether people compare options, we created two sequence types that differed in their relations between Adapt and Exchange: For one type, the sequential change was present in both the steps ratios for Adapt and Exchange (e.g., 1:1, 2:3, 3:1, etc.) as well as in the absolute steps needed for Adapt (e.g., 1, 2, 3, etc.). These sequences are called "linear" as Adapt steps increased or decreased linearly between trials (while Exchange steps remained constant). In the other type, the sequential change was only present in the steps ratios between Adapt and Exchange (e.g., 1:1, 2:3, 3:1, etc.), while subsequent trials alternated between high and low Adapt steps (e.g., 10, 4, 15, etc.). Hence, these sequences are called "mixed". If participants thoroughly compare Adapt and Exchange, sequence effects can be expected in both sequence types, because they are identical in the change of relations between the two options across trials.

Second, to investigate whether people perseverate on their past choices, sequence direction was manipulated: Ascending sequences started with a situation where Adapt was clearly preferable as the steps ratio between Adapt and Exchange was 1:1, while Adapt did not require the physical effort of conducting a module exchange. In subsequent trials, the steps ratios became less and less favorable for Adapt, until it was completely impossible to achieve conversion and avoid foam by merely adapting parameters. In contrast, descending sequences started with a situation in which Adapt was impossible and thus Exchange was mandatory, and then the steps ratio became more and more favorable for Adapt. Choice perseveration should be reflected in a continued choice of the initially preferred option.

Participants experienced the different sequences via curves that represented the relations between process parameters and the current conversion and foam thresholds. These thresholds as well as the initial parameter settings varied across trials, according to the respective sequence manipulation. An exemplar curve is shown in Figure 2. The left curve represents the current conversion threshold and its dependence on temperature and volume. All values above the curve meet the requirements. The right curve represents the threshold for foam risk and its dependence on temperature and mixing speed. All values below the curve are acceptable. Thus, to select appropriate pa-

Table 1. Definitions of the main concepts.

Concept	Definition
Direction (ascending, descending)	Change in the Adapt/Exchange ratio of costs over the course of a block. In ascending sequences, the option ratio starts out being 1:1 in the first trial and then progressively gets worse for Adapt until Adapt becomes impossible. In descending sequences, the option ratio starts out with Adapt being impossible in the first trial, much worse than Exchange in the second trial, and then progressively getting better until the option ratio reaches 1:1.
Sequence type (linear, mixed)	Change in the absolute costs of Adapt over the course of a block. In linear sequences, Adapt costs gradually get higher or lower (for ascending and descending sequences, respectively). In mixed sequences, Adapt costs alternate between high and low values.
Option ratio	Relative costs of Adapt and Exchange. For instance, an option ratio of 3:1 means that Adapt is three times costlier than Exchange, regardless of the absolute costs of the two options.
Absolute costs	Steps of process intervention required for an option. For instance, a cost level of 3 means that temperature and mixing speed have to be changed by three steps in total to reach the production goals (i.e., move above the conversion curve and below the foam curve).

rameter settings participants first had to determine a position above the left curve (conversion) by adjusting volume and/or temperature, and then transfer the new temperature value to the right curve (foam) to see if it is located below the curve. If not, they had to bring it below the curve by reducing mixing speed.

Hypotheses. The first research question was whether people carefully compare options or use a much simpler strategy of checking whether Adapt is good enough, and only consider Exchange when it is not. If people compare options, sequence effects should be observable in both linear and mixed sequences, because the change of the Adapt/Exchange ratio across trials is identical for both sequence types. Instead, if they focus on the absolute (instead of relative) number of Adapt steps, sequence effects should be restricted to linear sequences. First, across participants, the rate of Exchange choices at a given ratio should mirror the total number of required Adapt steps. This should lead to gradual increases of Exchange rates by ratio for linear sequences, but to Exchange rates with alternating local minima and maxima for mixed sequences. Second, the switch rate between options should be higher in mixed than linear sequences. This hypothesis is based on the assumption that in linear sequences people switch when the Adapt/Exchange ratio gets inacceptable (in ascending sequences) or acceptable (in descending sequences), and then stay with the new option for the remainder of the sequence. In contrast, we expected them to choose Exchange whenever the number of Adapt steps was high in mixed sequences, leading to frequent switches. Taken together, this leads to the following two hypotheses:

(1a) The percentage of Exchange choices gradually increases with ratio in linear sequences but alternates between low and high values in mixed sequences

(1b) Switch rates are higher in mixed than in linear sequences

The second research question was whether people perseverate on the options they have chosen. If so, there should be a difference in switch point position between ascending and descending sequences (i.e., hysteresis): When in ascending sequences participants start with trials favoring Adapt, they should switch from Adapt to Exchange at a higher ratio than they switch from Exchange to Adapt in descending sequences. That is, in ascending sequences they should stay with Adapt longer, while in descending sequences they should stay with Exchange longer. However, the trial number was very low (i.e., only one data point per combination of sequence type and direction). This was a necessary consequence of the fact that we wanted to study how participants actively implement their decisions in terms of specific parameter settings, which would have been impossible if we had changed the task to allow for higher trial numbers (e.g., by presenting fixed Adapt and Exchange solutions with set parameters and only asking participants to choose one of them). However, the low trial number limits the complexity of possible analyses. Therefore, we used the percentage of Exchange choices as a surrogate measure, expecting to find fewer Exchange choices in ascending than descending sequences. Moreover, as we hypothesized that participants might not detect the gradual ratio change in mixed sequences, we expected an interaction of sequence type and direction, indicating that the above-mentioned difference between ascending and descending sequences is restricted to linear sequences. Taken together, this leads to the following two hypotheses:

(2a) The percentage of Exchange choices is lower in ascending than in descending sequences

(2b) This difference is only found in linear sequences

Moreover, we conducted exploratory analyses of participants' parameter adjustments, but had no a priori hypotheses. Specifically, we wanted to investigate how much participants deviate from the minimally required process intervention (i.e., absolute Adapt and Exchange steps), whether and how this differs between sequence types and directions, and which parameters participants use preferably.

Methods

Participants

Overall, 51 members of the Technische Universität Dresden participant pool took part in the study in exchange for course credit (for students of Psychology) or 7€per hour (for all other participants). The majority of these participants were students of the Technische Universität Dresden from various disciplines. No participant had any experience with the process industries in general or modular plants in particular. Three participants dropped out for the following reasons: For

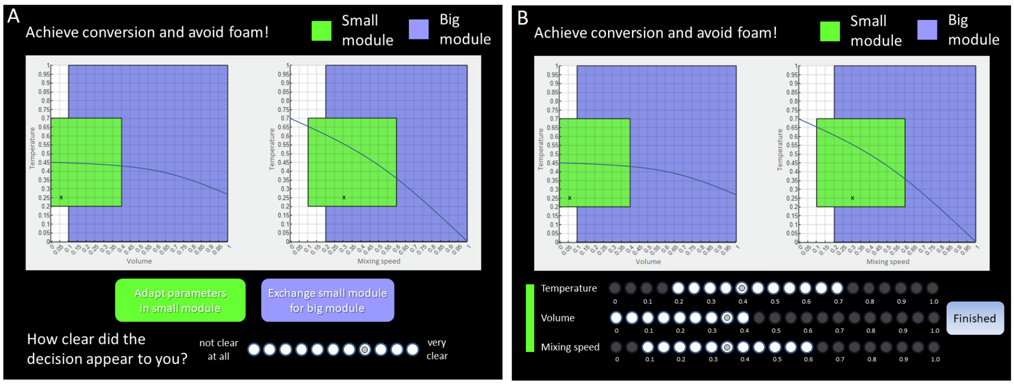

Figure 3. Stimulus material. (A) Choice screen. (B) Parameter adjustment screen. In the experiment, all text was presented in German.

one participant no data were recorded due to technical problems and two participants were not able to achieve the required conversion or to prevent foam in more than 50 % of the trials (80 and 97.5 % errors, respectively). Thus, the final sample comprised 48 participants (29 female) with an age range of 18 to 68 years (M = 27.8 years, SD = 9.9 years). Participants provided informed consent and all procedures followed the principles of the Declaration of Helsinki.

Apparatus and stimuli

Instruction seminar

Right before the experiment, each participant saw an instruction video of 17 minutes. The video was based on a Microsoft PowerPoint presentation. To facilitate learning, several instructional techniques were used, such as animations (Mayer & Moreno, 2003), advance organizers (Mayer, 2008), test questions (Nungester & Duchastel, 1982), and summary slides. The instruction seminar consisted of three parts:

(1) Explanation of the chemical process focusing on the causal relations between the process parameters (i.e., volume, temperature, and mixing speed) and the outcomes (i.e., conversion, foam)

(2) Introduction to modular plants and the different characteristics of the small and big module concerning the process parameters as well as the positive and negative effects of keeping the small module versus exchanging it for the big one

(3) Instruction concerning the materials, decisions, and possible actions in the experiment, as well as a set of heuristics for action selection: (1) parameter changes are risky for the product and thus change as few parameters as possible and change every single parameter as little as possible, (2) volume does not harm the process, (3) temperature is the most potent parameter with the strongest positive and negative effects, (4) often there is more than one correct solution.

In the part that provided an instruction about the experiment, the stimuli were explained in detail, along with a step-by-step procedural instruction on how to solve the task. Using a specific example with animations, the instruction stated that conversion was reached when the position of the x was above the left curve (see Figure 3) and that this meant that temperature had to be increased from value $T1$ to value $T2$. Moreover, it stated that in consequence of this temperature change, the x in the right picture moved to $T2$ as well and therefore was located above the foam curve now, although this change was not visible in the stimulus material. Accordingly, mixing speed had to be reduced from value $S1$ to $S2$. Importantly, the instruction did not refer to steps of process intervention but only named the initial and final parameter values. Also, it did not suggest any strategy for choosing between Adapt and Exchange, and instead used the same stimulus example to first demonstrate the procedure given that a person had chosen Adapt and then demonstrated it again given that a person had chosen Exchange. The instruction video (in German) is made available via the Open Science Framework: https://osf.io/5fcys/

Experiment

Experiments took place in a quiet lab room, using one of three notebooks (13.3" and 1366 × 768; 15" and 1920 × 1080; 15.6" and 1920 × 1080) and a standard computer mouse as an input device. The experiment was programmed using the Experiment Builder (SR Research, Ontario, Canada). All screens presented pictures, interaction elements, and text in white font on a black background, and consistent color coding was used for the small and big module (i.e., green and purple, respectively). In each trial, there were only two screens: a choice screen and a parameter adjustment screen. As each trial had its own stimulus material, 40 variants of these screens were created. The program for the experiment and our stimuli are provided via the Open Science Framework: https://osf.io/5fcys/

The *choice screen* (see Figure 3A) included the following elements: (1) a textual instruction to achieve conversion and avoid foam, (2) adjacent pictures of the current trial's process relations represented as conversion and foam curves, (3) a green button to choose Adapt and a purple button to choose Exchange, and (4) a 10-point scale to rate how clear the decision had

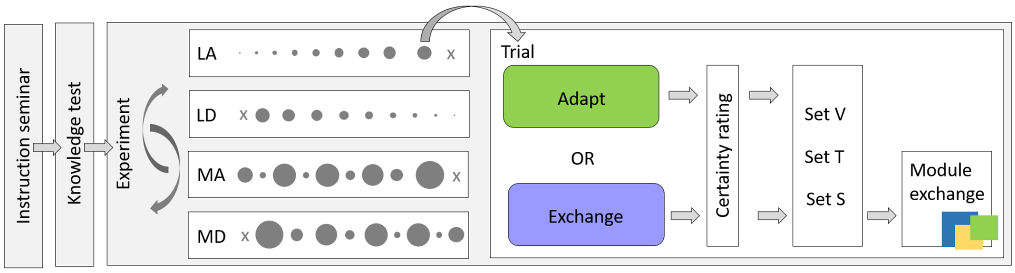

Figure 4. Overview of the procedure. Dots represent individual trials, and dot size represents the number of required Adapt steps. The curved arrows next to the blocks indicate that block order was counterbalanced across participants (see text for details). L = linear, M = mixed, A = ascending, D = descending, V = volume, T = temperature, S = mixing speed.

appeared to participants, ranging from *not clear at all* to *very clear*. Relations for conversion and foam were presented on the same screen and the same curve applied to both modules. Most importantly, each relation picture reflected the interaction of two parameters in terms of its effect on one outcome: For conversion (left hand side), the relation between temperature on the y-axis and volume on the x-axis reflected the ability of each parameter value combination to exceed the conversion threshold, which was represented as a curve. Thus, all positions above the curve corresponded to parameter value combinations suitable for meeting the conversion requirement, while all positions below the curve corresponded to non-suitable combinations. Similarly, for foam (right hand side) the relation between temperature on the y-axis and mixing speed on the x-axis reflected the ability of each combination to stay below the acceptable foam risk. Thus, all combinations below the curve were suitable for meeting the foam requirement, while all positions above the curve were non-suitable. The direction of relations between temperature/volume to conversion and temperature/mixing speed to foam were the same throughout the experiment, while curve slopes and curvatures differed between trials. In all graphs, green and purple rectangles visualized the parameter value ranges of the small and the big module, respectively. These ranges were fixed throughout the experiment. The current parameter settings were represented as a black x on both sides.

The *parameter adjustment screen* (see Figure 3B) was similar to the choice screen, but the choice buttons and rating scale were replaced by three rows of 20 radio buttons to set temperature, volume, and mixing speed in steps of 0.5 units. Parameter ranges were standardized from 0 to 1 for all parameters. Only radio buttons representing possible parameter settings within each module were clickable, while the others were overlaid with grey shading. Upon the screen's appearance, no parameter values were selected. The visualization of the curves and current value position remained stable throughout a trial and thus did not change as a function of time or participants' inputs. To the right of the radio buttons, a 'finish' button allowed participants to proceed to the following trial or prompt for the physical module exchange task.

The *physical exchange of modules* was simulated using Mega Bloks (i.e., big, colored plastic blocks that can be stacked). A small green stack represented the small module and a big purple stack represented the big module. To support participants in performing the exchange sequence, a three-page instruction was made available to them, demonstrating each step of the sequence with a picture and corresponding textual explanation (for contents see Figure 5).

Procedure

Upon arriving in the lab, participants received a written briefing that explained the general purpose of the present study (i.e., investigate how people make decisions in modular plant scenarios) and its procedure (i.e., instruction seminar, knowledge test, experiment). The study consisted of an instruction seminar including a knowledge test and the actual experiment. An overview of the procedure is provided in Figure 4.

Instruction seminar

Before the experiment, participants went through an instruction seminar, completed five practice trials on paper, and then performed a written knowledge test assessing their understanding of the seminar contents. While all participants were allowed to complete the experiment, a criterion of 70% correct answers was used to decide whether the data would be analyzed or replaced by a new participant. However, all participants passed. Taken together, the instruction and knowledge test took about 30 minutes.

Experiment

Up to three participants worked in parallel during each session. Before starting the actual experiment, participants were shown the physical module exchange procedure and then had to work through it by themselves. The experiment consisted of four blocks of ten trials. Blocks corresponded to the combinations of sequence type and direction (see Table 2). Block order was counterbalanced across participants, with the constraints that sequence type was varied between the experimental halves and the same order of directions was used in both halves. Accordingly, four orders were used (L = linear, M = mixed, A = ascending, D = descending): $[LA+LD+MA+MD]$, $[LD+LA+MD+MA]$, $[MA+MD+LA+LD]$, $[MD+MA+LD+LA]$.

Table 2. Ratios and absolute step numbers required for *Adapt* and *Exchange* depending on sequence type and direction.

	Linear						Mixed					
	Ascending			Descending			Ascending			Descending		
Trial	A/E	A	E	A/E	A	E	A/E	A	E	A/E	A	E
1	1:1	1	1	imp	imp	1	1:1	10	10	imp	imp	2
2	2:1	2	1	9:1	9	1	2:1	4	2	9:1	18	2
3	3:1	3	1	8:1	8	1	3:1	15	5	8:1	8	1
4	4:1	4	1	7:1	7	1	4:1	4	1	7:1	14	2
5	5:1	5	1	6:1	6	1	5:1	15	3	6:1	6	1
6	6:1	6	1	5:1	5	1	6:1	6	1	5:1	15	3
7	7:1	7	1	4:1	4	1	7:1	14	2	4:1	4	1
8	8:1	8	1	3:1	3	1	8:1	8	1	3:1	15	5
9	9:1	9	1	2:1	2	1	9:1	18	2	2:1	4	2
10	imp	imp	1	1:1	1	1	imp	imp	2	1:1	10	10

Note. A/E = *Adapt/Exchange-Ratio; A = Adapt; E = Exchange; imp = impossible.*

In ascending sequences, the ratio between the process intervention required for Adapt and Exchange started at 1:1 and then increased across trials. Process intervention was defined as the sum of temperature and mixing speed steps (with each step corresponding to 0.5 units) that were needed to achieve conversion and avoid foam. Thus, relative to Exchange, Adapt became more and more costly, until in the tenth trial it was impossible to solve the task in the current small module. Conversely, descending sequences started with a scenario in which Adapt was impossible and in subsequent trials the ratio got smaller until it reached 1:1 in the 10th trial. Thus, the disadvantage of Adapt was gradually reduced until it was absent. The stimuli used in ascending sequences for half of the participants were used in descending sequences for the other half, and vice versa.

In linear sequences, the ascending or descending ratio was identical to the total number of Adapt steps. In consequence, when a sequence was ascending, not only the ratio between Adapt and Exchange got less favorable for Adapt but also the absolute number of required Adapt steps got bigger and thus more and more process intervention was needed to solve the task in the current module. Conversely, in mixed sequences only the ratio of Adapt and Exchange changed gradually, while the absolute number of required Adapt steps moved up and down every other trial. Thus, while in ascending sequences Adapt still became worse relative to Exchange, its absolute cost varied. All ratios and absolute step numbers of both options in each block are presented in Table 2.

An inspection of the table also reveals that mixed sequences required higher absolute step numbers overall than linear sequences. This difference between sequence types was necessary for practical reasons, resulting from the fact that the use of radio buttons made rounding impossible and thus limited the set of possible values. Note that this makes some main effects of sequence type hard to interpret. Sequence variants and stimuli differed in their assignment of total step numbers to temperature and mixing speed. For instance, a step number of 6 could mean a required temperature increase of 5 and a mixing speed decrease of 1, or a temperature increase of 2 and a mixing speed decrease of 4. Stimuli also differed in the number of volume steps required, although volume was not included in the step number calculation.

Each trial started with a presentation of the choice screen on which participants saw the current relation curves and planned their choice and parameter adjustment. Once they had made a decision between Adapt and Exchange, they had to indicate how clear it had appeared to them on a 10-point scale. After this rating, the Adapt and Exchange buttons became clickable and clicking them transferred participants to the respective parameter adjustment screen. On this screen, they could set all three parameters and then press the ‘finish’ button to complete the trial or go to the physical module exchange task. The ‘finish’ button only became active after all three parameter values had been set. No performance feedback was provided. On average, one trial took 61.8 s.

If participants chose Exchange, they had to perform a physical module exchange procedure after finishing their parameter settings, using a simplified plant setup constructed with Mega Bloks (see Figure 5). During this procedure, they had to exchange the small green module for a big purple module in a fixed sequence of ten steps. The procedure was designed to reflect several characteristics of tasks in modular plants such as assembling and de-assembling equipment, sequential performance, and waiting. On average, it took participants 39.4 s to complete this task. After they had completed the module exchange, the experimenter reversed it while participants resumed their work in the next trial.

The experiment concluded with an interview about participants' strategies. Afterwards, they were offered a verbal debriefing about the aims of the study (i.e., investigating whether people compare options and whether they perseverate on previous choices) and ~~the~~ how this translated to the experimental manipulations. Altogether, the experiment took between one and two hours, with large variations between participants.

An overview of the descriptive results is presented in Table 3 and correlations between dependent variables are presented in Table 4. Statistical comparisons between the experimental conditions were performed using analyses of variance (ANOVAs), and the factors included in each analysis are specified in the respective sections. An alpha value of $\alpha = .05$ was used to determine statistical significance, and all pairwise comparisons were performed with Bonferroni correction. All data is made available via the Open Science Framework: https://osf.io/5fcys/

Results

Choice of options

To investigate how participants chose between Adapt and Exchange, the percentage of Exchange and the switch rate were analyzed using 2 (*sequence type*: linear, mixed) × 2 (*direction*: ascending, descending) repeated measures ANOVAs.

Percentage Exchange

The percentage of Exchange reflects how often participants exchanged modules within a sequence. There was a main effect of sequence type, $F(1, 47) = 42.1, p < .001, \eta_p^2 = .47$, and a main effect of direction, $F(1, 47) = 33.7, p < .001, \eta_p^2 = .42$, but no interaction, $F(1, 47) = 1.90, p = .18, \eta_p^2 = .04$ (see Figure 6A). Participants exchanged more often in mixed than linear sequences (36 vs. 22 %), although this result is hard to interpret as mixed sequences required higher step numbers overall. Most interestingly, and contrary to our hypotheses, participants also exchanged more often in ascending than descending sequences (33% vs. 24%). This preference for Exchange in ascending sequences was not only present in mixed but also in linear sequences, both $ps < .008$, while for the latter we had expected fewer Exchange choices in ascending than descending sequences.

To better understand this surprising result, Figure 7A and B plot the required steps for Adapt and Exchange for each ratio while Figure 7C and D plot the respective percentages of Exchange choices. It appears that in ascending linear sequences, participants started exploring Exchange quite early. In contrast, for descending linear sequences it seems that after having experienced their first trial in which Exchange had been necessary and Adapt had been impossible, they switched away from Exchange as soon as Adapt became possible in trial 2, and stayed with Adapt more often throughout the remainder of the sequence. Another hypothesis had been that Exchange choices would mirror the absolute step numbers required for Adapt, instead of the Adapt/Exchange ratio. Therefore, it is interesting to compare the percentage of Exchange in the mixed sequences (Figure 7D) to the number of steps required for Adapt (Figure 7B, green line). Especially for ascending mixed sequences, a close correspondence can be observed.

Switch rate

The switch rate reflects how often participants alternated between choosing Adapt and Exchange within a ten-trial sequence. As the first trial can neither be a repetition nor a switch, the maximum switch rate is 90%. There were main effects of sequence type, $F(1, 47) = 12.2, p = .001, \eta_p^2 = .21$, and direction, $F(1, 47) = 6.54, p = .014, \eta_p^2 = .12$, but no interaction, $F < 1$ (see Figure 6B). In line with our hypotheses, participants switched between Adapt and Exchange more often in mixed than linear sequences (33% vs. 24%). Unexpectedly, they also switched more often in ascending than descending sequences (31% vs. 26%). For linear sequences, we had expected participants to choose one option at the start of a sequence and then at some point switch to the other option to stay there for the remainder of the sequence. As can be seen in Figure 8, participants rarely did that but repeatedly switched between the options throughout the sequence. Overall, 60 of the 192 sequences (31.3%) contained only one switch, but most of these one-switch sequences reflect that participants only used Exchange when Adapt was impossible in the first or last trial, while there were only nine sequences (4.7%) in which participants performed a single switch at a position where it was not needed.

Decision time

The decision time or time to choose an option was computed as the time from the onset of the choice screen until either the Adapt or Exchange button was clicked. On average, participants took 24.1 s to make their choice. To investigate how this time varied between the experimental conditions, a 2 (*sequence type: linear, mixed*) × 2 (*direction: ascending, descending*) repeated measures ANOVA was computed. As expected, neither the main effects nor the interaction were significant, all $Fs < 1$.

In the next step, we analyzed how decision times depended on whether participants chose Adapt or Exchange. This was done to further investigate the hypothesis that participants do not systematically compare options but first check whether Adapt is good enough, and only compute an Exchange solution when it is not. If they compare options, decision times should not differ between Adapt and Exchange trials as both options would be computed regardless of which one is ultimately chosen. In contrast, if participants only compute a solution for Adapt and then choose Adapt when satisfied with this solution, deci-

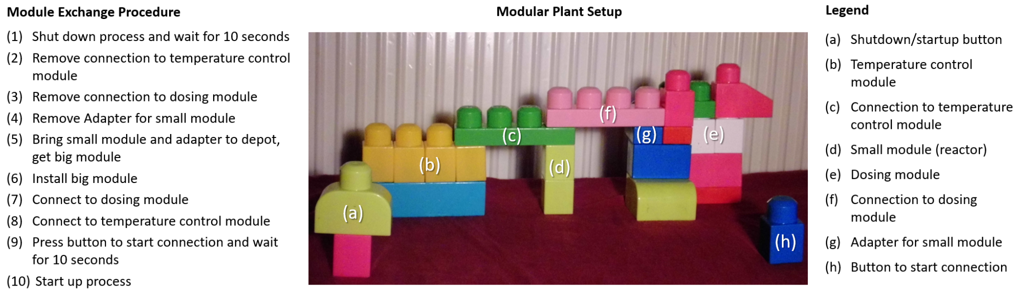

Figure 5. Procedure for the physical exchange of modules.

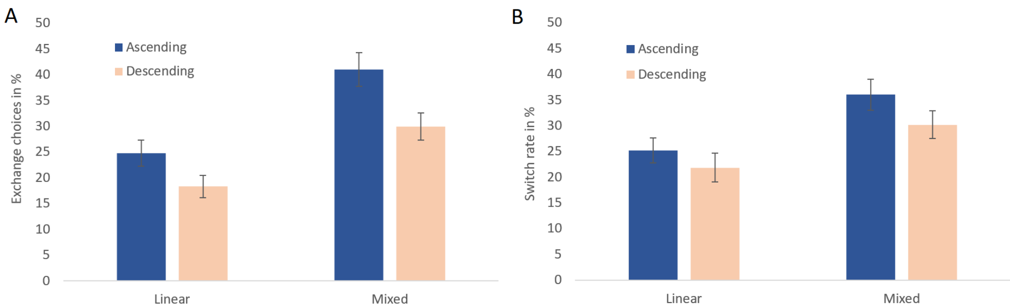

Figure 6. Decisions as a function of sequence type and direction. (A) Percentage of Exchange. (B) Switch rate. Error bars represent standard errors of the mean.

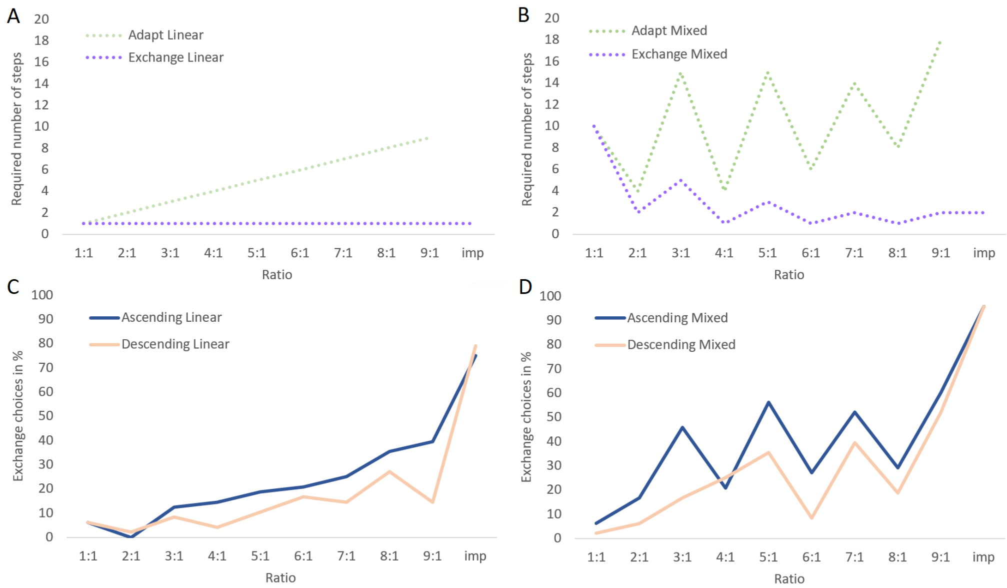

Figure 7. Influences of ratio and absolute process intervention (step number) required for each ratio. The top row shows the numbers of steps (i.e., temperature, mixing speed) that are necessary to achieve conversion and avoid foam depending on whether Adapt or Exchange is chosen for (A) linear sequences and (B) mixed sequences. The bottom row shows participants' Exchange rate for (C) linear sequences and (B) mixed sequences. Note that for ascending sequences the ratios on the x-axes represent trial positions (1 – 10), while for descending sequences the graphs have to be read backwards.

Table 3. Mean values and standard deviations (in parentheses) for all dependent variables, depending on sequence type and direction.

		Linear		Mixed	
		Ascending	Descending	Ascending	Descending
Decision making					
Percent *Exchange* (%)		24.8 (17.7)	18.3 (15.1)	41.0 (22.9)	30.0 (18.3)
Switch rate (%)		23.6 (23.8)	16.0 (22.8)	25.7 (28.6)	17.4 (23.8)
Decision time (s)	*Adapt*	20.3 (11.5)	20.4 (15.5)	25.8 (17.1)	22.1 (11.7)
	Exchange	27.6 (15.6)	40.2 (43.7)	23.9 (13.1)	33.7 (19.3)
Parameter settings					
Deviation from min with V	*Adapt*	0.54 (0.66)	0.35 (0.84)	0.49 (0.59)	0.28 (0.55)
	Exchange	1.83 (2.01)	1.93 (2.59)	1.94 (3.26)	2.32 (3.78)
Deviation from min without V	*Adapt*	1.49 (1.66)	1.12 (1.71)	1.57 (1.40)	1.20 (1.31)
	Exchange	0.85 (3.53)	1.43 (2.48)	0.78 (3.05)	1.12 (2.50)

sion times should be shorter for Adapt choices. To differentiate between these possibilities, the factor *option* (Adapt, Exchange) was added to the ANOVA. In consequence, ten participants could not be included as they never chose Exchange in at least one of the sequences. Thus, the analysis was performed with 38 participants. There was a significant main effect of option, $F(1, 37) = 17.2, p < .001, \eta_p^2 = .32$, an interaction of option and sequence type, $F(1, 37) = 8.44, p = .006, \eta_p^2 = .19$, and an interaction of option and direction, $F(1, 37) = 9.29, p = .004, \eta_p^2 = .20$. In contrast, the three-way interaction was far from significance, $F < 1$ (see Figure 9). The time until choosing an option was shorter for Adapt than Exchange choices (22.1 s vs. 31.4 s) . This Adapt benefit was stronger in linear than mixed sequences but significant for both, both $ps < .012$. Moreover, it was reliable only for descending sequences, $p = .001$, but missed the significance level for ascending sequences, $p = .06$.

Parameter settings

Another aim of the study was to explore how participants adjusted the process parameters and how this depended on sequence type and direction. Therefore, the deviation from minimal intervention was calculated as the difference between the number of temperature and mixing speed steps used by participants and the number of steps required to achieve the goals. The factor *option* was included as fewer steps were required for Exchange than Adapt, and therefore the deviation was expected to also be smaller for Exchange. A 2 (*option*: Adapt, Exchange) × 2 (*sequence type*: linear, mixed) × 2 (*direction*: ascending, descending) repeated measures ANOVA was computed. Including the factor option again led to a loss of ten participants, so the analysis was performed with 38 participants. It revealed a main effect of option, $F(1, 37) = 17.6, p < .001, \eta_p^2 = .32$, while no other main effects or interactions were significant, all $Fs < 3$, all $ps > .09$. Unexpectedly, deviations from minimal intervention were five times higher for Exchange than Adapt (2.01 steps vs. 0.41 steps), regardless of sequence type and direction (see Figure 10A). A possible explanation is that in spite of the instructions stating that volume had no negative effects, participants might have treated volume like any other parameter, preferring medium volume changes combined with medium temperature changes to big volume changes combined with small temperature changes. In this case, the difference between Adapt and Exchange should disappear when the minimal required intervention and deviation from it are re-calculated to include volume. Indeed, the main effect of option disappeared, $F(1, 37) = 1.99, p = .17, \eta_p^2 = .05$, indicating that deviations from minimal intervention no longer differed between Adapt and Exchange (1.35 steps vs. 1.05 steps, see Figure 10B). No other main effects or interactions were significant, all $Fs < 2$, all $ps > .16$, except for an interaction of option and direction, $F(1, 37) = 4.80, p = .04, \eta_p^2 = .12$. This interaction reflected that for ascending sequences, Adapt produced higher deviations than Exchange, $p = .02$, while for descending sequences there was no difference, $p > .70$.

A qualitative analysis of individual strategies in parameter adjustments was performed by overlaying the submitted parameter settings on each of the 40 stimulus pictures, as illustrated in Figure 11. First, participants differed in whether they used the full range of volume: Some maximized volume in the small module even when they would also have landed above the curve without it, while others did not use volume at all in the same situation, and again others adjusted it just a bit. Second, participants differed in how they combined volume and temperature: When choosing Exchange, some participants increased volume as much as necessary to allow for minimal temperature increases. In contrast, others only used medium changes of volume even when this meant they had to make a medium temperature change as well, completely ignoring that temperature was potentially harmful while volume was not. Additional analyses not reported in the present article revealed that successful par-

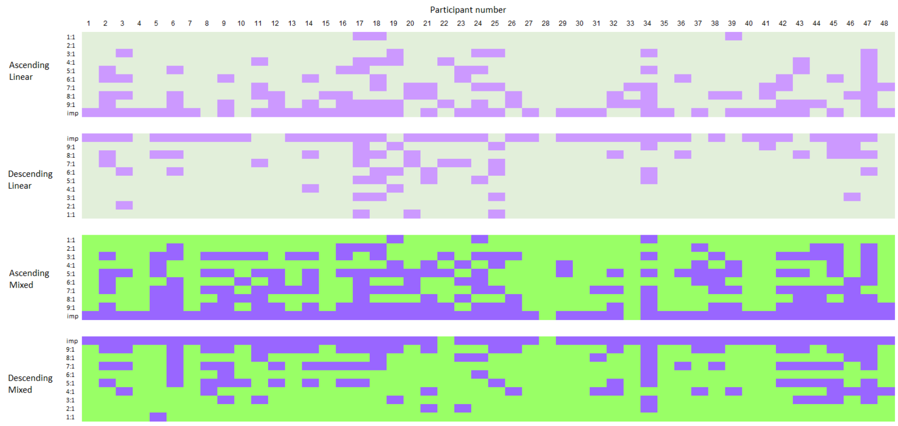

Figure 8. Individual participants' Adapt and Exchange choices for each ratio (aligned vertically according to the order of trials) in all combinations of sequence type and direction. Adapt choices are presented in green and Exchange choices in purple, while light colours indicate linear and dark colours indicate mixed sequences. Each field represents one trial.

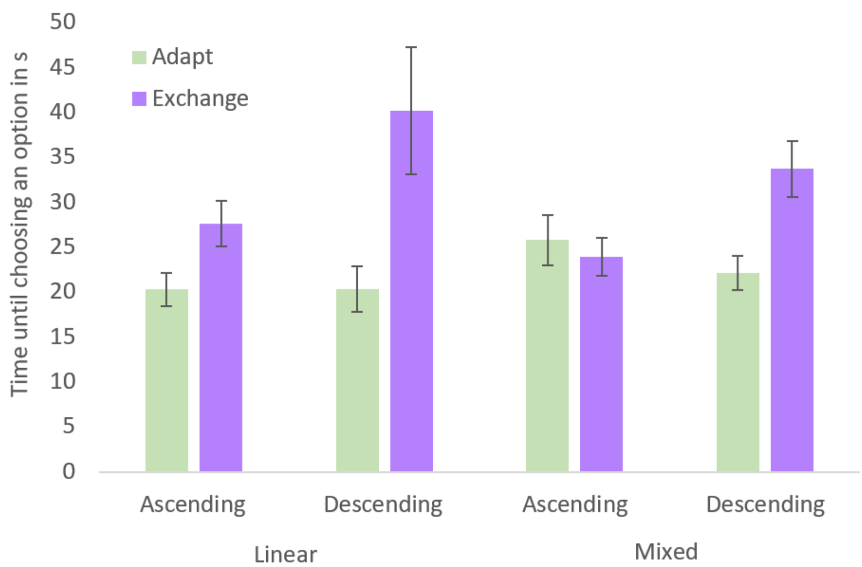

Figure 9. Decision time depending on sequence type, direction, and option. Error bars represent standard errors of the mean.

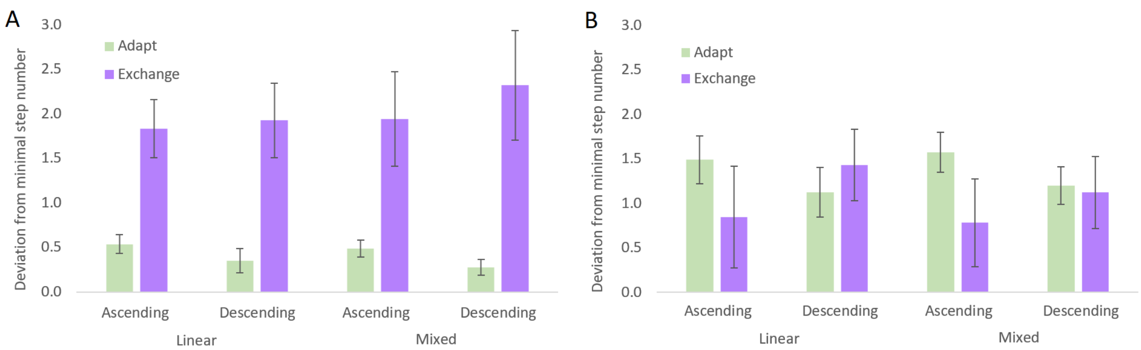

Figure 10. Deviation from minimal process intervention depending on sequence type, direction, and option (A) without volume and (B) with volume included in the calculation. Error bars represent standard errors of the mean.

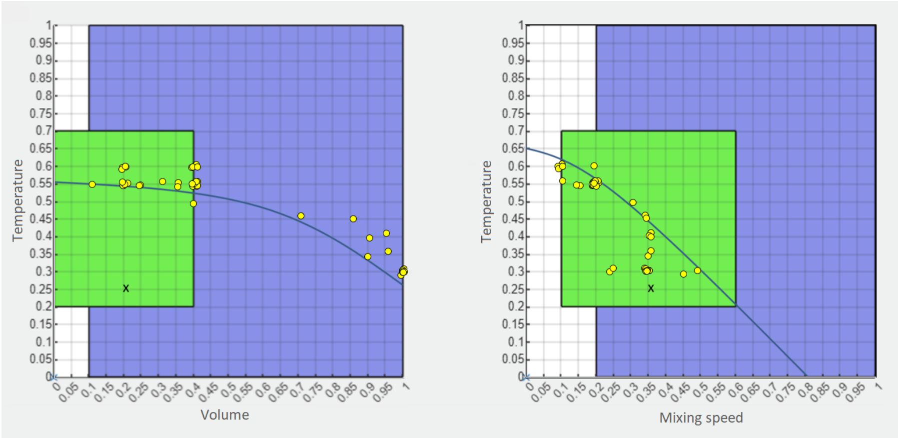

Figure 11. Strategy example. Yellow dots represent individual participants' parameter settings. Jitter was added to facilitate the visual differentiation of data points, while in the experiment participants could only set parameters in steps of 0.5 units (i.e., to grid intersections).

ticipants (i.e., with above average rates of achieving both production goals) were those who made large volume adjustments but small temperature adjustments when choosing Exchange. Finally, some participants made parameter adjustments that cannot be explained within the logic of the task (e.g., increasing mixing speed).

Discussion

In everyday life, people are often faced with the question of whether they should only make minor adaptations to the status quo or fundamentally change the situation. Such decisions require a balance between stability and flexibility in order to determine how long to stick with mere adaptations and how thoroughly to consider alternative options. Many previous studies have contributed to our knowledge about how people balance stability and flexibility by investigating how they compare options and whether they repeat previous choices. However, previous studies do not provide much insight into the processes of choosing between qualitatively different options. Therefore, the present study aimed to extend research from the decision making literature on the stability-flexibility balance to decision environments with more complex problem structures. To this end, we investigated decisions in which people either choose to only make modifications to the current context or switch the context as such: In a modular plant scenario, participants could either adapt parameters in the current module or exchange the module for a more suitable one. We varied sequence type (i.e., linear vs. mixed) to investigate whether participants thoroughly compare options, and sequence direction (i.e., ascending vs. descending) to investigate whether they perseverate on their previous choices. The results revealed that in mixed sequences, participants switched options more often and their rate of Exchange choices mirrored the required Adapt steps, suggesting that they did not consider option ratios but focused on absolute Adapt steps instead. In line with this interpretation, Exchange choices took more time, raising the possibility that they included an additional mental operation (i.e., computing an Exchange solution) that was not carried out when choosing Adapt. In ascending sequences, participants chose Exchange more often, which is at odds with the expected choice perseveration. Analyses of parameter settings revealed a variety of different strategies for implementing choices. In the following sections, we discuss these results in relation to the research questions, which organize the first three sections. We then examine the characteristics of decisions in modular plants, from which we proceed to discussing the balance between psychological rigor and real-world problem structures in the study of decision making. Finally, we outline perspectives for future research.

Do people thoroughly compare options?

One aspect of balancing stability and flexibility is that people need to decide how thoroughly they should consider alternative options. In the context of modular plants, this raises the question whether people actually compare Adapt and Exchange or merely check whether Adapt is good enough. In the present study, increased switch rates in mixed sequences and longer decision times for Exchange choices suggest that participants did not compare Adapt and Exchange with regard to their respective process interventions. Instead, it seems like they checked how much process intervention was needed for Adapt, and only considered Exchange when this intervention seemed too high. This behavior corresponds to the simple decision strategy of satisficing (Simon, 1956), where people merely check whether an option is good enough instead of comparing options.

Why did participants not compare options? In paradigms investigating the choice between asymmetric options (e.g., delay discounting), even models that assume decisions to be based on simple heuristics take it for granted that people consider the absolute and relative differences between options (Ericson, White, Laibson, & Cohen, 2015). A possible explanation lies in the demands of the comparisons required in the present task. In typical studies of asymmetric choice,

Table 4. Correlations between dependent variables (N = 48).

	1	2	3	4	5
1. Percentage Exchange (%)	1				
2. Switch rate (%)	.81**	1			
3. Decision time (s)	.40**	.37**	1		
4. Deviation from min with V	-.42**	-.25	-.10	1	
5. Deviation from min without V	-.14	.03	.00	.63**	1

Note. ** correlation significant at the .01 level (2-tailed)

the attributes are easy to perceive and compare (e.g., two amounts of money and two time delays = four numbers). Conversely, in the present study comparisons required an effortful computation and combination of spatial distances from the left and right process graphs. Thus, the difference in step numbers for Adapt and Exchange could not possibly be estimated at a glance, which can impair option comparison (Glöckner & Betsch, 2008).

The difficulty of information integration reflects a central domain characteristic of the process industries (Müller & Oehm, 2019; Mumaw, Roth, Vicente, & Burns, 2000). Presumably, also in other domains there are few situations in which all information about the options and their attributes is laid out neatly so that the decision maker can integrate it at a glance. Therefore, we suggest that the present structure of information presentation (although not its surface features) actually is quite common. However, it differs from many decision making experiments that use much simpler forms of information presentation. Task difficulty is among the main situational factors to encourage satisficing (Krosnick, 1991). In line with this finding, satisficing is common in complex tasks such as chemical process operation, but not in typical lab tasks. Thus, it might be that most psychological studies are too easy to induce the decision making processes that characterize many real-world tasks.

Do people perseverate on previous choices?

A second aspect of balancing stability and flexibility is that people might either evaluate each new situation anew, regardless of the decision history, or stick with their previous choices. The latter strategy should lead to sequence effects in the form of repeated choices of the initially chosen option, even when it becomes less suitable. However, in the present study effects of sequence direction were opposite to the hypothesized choice perseveration: In ascending-linear sequences, participants exchanged more overall and seemed to start exploring Exchange early on in the sequence. Conversely, in descending-linear sequences they moved away from Exchange from the second trial onwards, as soon as Adapt became possible. Similar conclusions can be drawn from the unexpected lower switch rates in descending than ascending sequences. A major contributor to this finding is that in descending-linear sequences 25 participants (52.2%) never chose Exchange in trials where it was not needed, and thus never went back to Exchange after the first trial.

Overall, switch rates in linear sequences were quite high (about 25%), showing that our initial idealized assumption of a singular switch to Exchange (in ascending sequences) or to Adapt (in descending sequences) was not supported by the data. Instead, participants switched back and forth between the options much more than expected, while sequence effects only existed on a group level with aggregated data. Accordingly, aftereffects of the previous decision (e.g., choice perseveration) do not provide a valid explanation, because a minimal requirement for such explanations was not fulfilled: that the effects rely on the choice history from previous trials. Obviously, one can only experience aftereffects from one's own previous choices, not from the aggregated choices of other participants. Unfortunately, we do not know whether the absence of actual aftereffects is a particularity of the present study, because previous studies only reported aggregated data (Scherbaum et al., 2016; Schoemann & Scherbaum, 2017; Senftleben et al., submitted; Senftleben et al., 2019). An interim conclusion is that ascending-linear sequences led participants to explore Exchange, while descending-linear sequences discouraged Exchange after it had been inevitable – or encouraged Adapt as soon as it became possible.

Notably, not all other studies found evidence for choice perseveration either, or even found the opposite in delay-discounting tasks (Becker, 2018; Robles & Vargas, 2008; Robles, Vargas, & Bejarano, 2009). Comparing the results of different studies is difficult as they strongly differ in their implementation of ascending and descending sequences. For instance, in some studies an ascending sequence implies that options become more similar on the attribute defining the sequence, while in others they become more different, or in some studies the preferred option gets worse while in others the dispreferred option gets better. However, several determinants of choice perseveration have been suggested in the literature. First, choice perseveration does not depend on whether the sequential change is realized via changes in cost, value, or a combination of both (Schoemann & Scherbaum, 2017). Thus, observing choice perseveration should have been possible in the present study, where the options only changed in costs (i.e., required process intervention). Second, choice perseveration only occurs with intermediate value ratios, while it is absent when one option is much more attractive (Scherbaum et al., 2016). This constitutes a potential explanation for the present results: Adapt was preferred overall, and even at a ratio of 9:1 the percentage of Exchange choices did not reach the indifference point of 50%. Third, it has been proposed that choice perseveration might be absent when sequence manipulations are too obvious (Scherbaum et al., 2016). This suggestion has not been tested, but if it is valid, it cannot account for the present results as the high switch rates suggest that sequences were all but obvious. Finally, choice perseveration depends on the timing within and between trials, and can disappear as a consequence of subtle manipulations of inter-trial interval or stimulus onset asynchrony (Senftleben et al., submitted; Senftleben et al., 2019). The latter findings suggest that the effects found in previous studies rely on quick, spontaneous responding and might not be generalizable to more complex decisions.

Why did we observe sequence effects opposite to choice perseveration? A possible explanation is that in linear-descending sequences participants switched as soon as the initially chosen option was no longer mandatory, or another option became possible. The first version, moving away from an option that has been mandatory, neatly fits with the finding that choice perseveration is stronger after free than after forced choices (Alós-Ferrer et al., 2016). As Adapt was impossible in the first trial of descending sequences, choosing Exchange was comparable to a forced choice, which might account for the drop in Exchange choices in the subsequent trial. A second explanation for the sudden drop in Exchange choices is that participants wanted to choose a previously unavailable option as soon as it became possible. For consumer choices, unavailability can make options appear more desirable (Lynn, 1991). Similar findings stem from the literature on phantom alternatives (Pratkanis & Farquhar, 1992), which are options that look real but are unavailable (e.g., due to time or budget restrictions). Their presence makes the attributes on which they are preferable seem more important and makes the available options seem less attractive. Applied to the present study, in descending sequences participants have already seen a trial with "real" constraints (resulting in Adapt being impossible), and this might change their perception of what counts as a situation that requires Exchange. Thus, in future situations with less harsh constraints, the reasons for choosing Exchange may be lacking. Note that this explanation cannot account for all sequence effects reported in the literature. Instead, it is specific to decisions that are not merely a matter of preference but need to consider certain contextual constraints. Although this is common for many real-world decisions, it has not played any role in the psychological literature on sequence effects in decision making so far.

Finally, a more conceptual question that should be addressed is what it actually means to perseverate. Does it mean to repeat previous choices or to choose Adapt, irrespective of previous choice? That is, perseveration can also be conceptualized as staying within the current context (i.e, module). When using the latter conceptualization, perseveration might actually have occurred in the present study, because the overall Exchange rate was only 28.5%. However, it gets even more complicated: Even with a context-centered instead of a choice-centered conceptualization of perseveration there is no unambiguous way of associating it with Adapt. Instead, it depends on whether you consider the plant state (i.e., using the same module) or the process state (i.e., keeping parameter settings close to their initial values). Under the latter conceptualization, Adapt actually represents a bigger change. Accordingly, perseveration is a matter of perspective, depending on the means-end level in the Abstraction Hierarchy (Rasmussen, 1985) that is chosen for evaluation – physics or function. This is just one of many examples for the dependence on perspective, and more will be discussed later. For now, it suffices to note that once we leave the small and tidy world of psychology experiments, decision phenomena that seem straightforward (e.g., perseveration) can suddenly become quite complex.

How do people adjust process parameters to implement their choices?

Explorative analyses of participants' parameter adjustment strategies led to several interesting observations. First, participants deviated from the minimal required process intervention more strongly when implementing their Exchange choices than their Adapt choices. This puzzling result turned out to be a consequence of excessively using temperature, presumably as a way to keep volume increases low. Despite being instructed that volume changes do not harm the process, some participants opted for a balanced use of volume and temperature. This is in line with the phenomenon of extremeness aversion in decision making, which reflects that people prefer intermediate options (Simonson & Tversky, 1992). In the present study they could craft these options by themselves via more balanced parameter adjustments. This is what several participants did, although additional analyses revealed that it led to fewer successful outcomes. Moreover, it needs to be noted that some parameter adjustments did not seem to make sense at all, for instance when participants increased mixing speed although this had no positive effects.

Taken together, when decision making is not a one-shot activity but people have to implement their choices, much can be gained from analyzing these implementations in detail. A side-effect is that such scenarios can make it quite hard to interpret choice behavior in isolation. For instance, when only looking at the high switch rates in linear sequences, one might assume that participants were acting randomly, while an analysis of their parameter settings clearly refutes this concern. Accordingly, a curious question is to what degree this also pertains to psychology experiments in which option implementation is not an explicit part of the study. The latter does not mean that participants do not consider implementation when making their choices, and such imagined implementations might affect their decisions, leading to behavioral effects that are hard to interpret.

Balancing psychological rigor and real-world problem structures

Adapt and Exchange represent qualitatively different options. To illustrate the difference to typical psychological studies of decision making, consider the example of delay discounting where people choose between smaller-sooner and larger-later rewards (Berns et al., 2007; Frederick et al., 2002). Superficially, the decision context looks similar to Adapt/Exchange decisions: For smaller-sooner rewards, you do not have to invest much (i.e., not wait for long) but you also do not get much in return. This seems comparable to the consequences of choosing Adapt, while larger-later rewards seem to resemble Exchange. However, this comparison is quite arbitrary. You could equally interpret Exchange as the easy option, because after all, the goals can be achieved with minimal process intervention: simply increase temperature a little and you are done. Thus, depending on the goals you consider (e.g., minimize physical effort vs. minimize process intervention), the characterization of options can change dramatically, even on the same abstract attribute (i.e., costs). Psychological studies usually do not include such degrees of freedom in perspective but use a single operationalization of value (i.e., reward) and one of costs (e.g., delay, risk, or effort).

Instead, in the present study different conceptualizations of costs operated at the same time, and participants might have differed in their focus on either of them. This is important as different costs imply different types of discounting (e.g., temporal, probability, and effort discounting). Previous research suggests that these types rely on separate mechanisms (Green & Myerson, 2004). For instance, they differ in how the amount of reward affects discounting (Białaszek, Ostaszewski, Green, & Myerson, 2019; Estle, Green, Myerson, & Holt, 2006; Myerson, Green, Hanson, Holt, & Estle, 2003). Factor analyses have revealed that temporal and effort discounting load on the same factor, while probability discounting loads on another (Białaszek et al., 2019). Similarly, correlations between temporal and probability discounting are weak or absent (Myerson et al., 2003; Shead & Hodgins, 2009). In consequence, whether people evaluate the costs of Adapt and Exchange in terms of effort or risk is likely to affect their decisions. More generally, this should caution us against directly relying on the psychological literature to evaluate decision making between qualitatively different options.

The previous sections have alluded to a number of difficulties resulting from the complex decision context of the present study. Can these difficulties be eliminated by simply using more controlled experimental settings to study Adapt/Exchange decisions? In a recent review of dynamic decision making, Gonzalez et al. (2017) concluded that relevant psychological processes of decision making in complex, dynamic systems can be studied in simple tasks. Probably, this is true if you are mainly interested in basic cognitive mechanisms, independent of domain content. However, it raises the question what such studies can contribute to our understanding of decision making challenges in complex settings such as modular plants. Even the present study was extremely simple from a domain perspective, and many characteristics of modular plants have not been addressed even remotely. For instance, multiple goals within the same category are the norm rather than the exception in the process industries: Decision makers have to balance the risks and costs of harming the plant, destroying the product, missing deadlines, wasting too much energy, and several others.

Accordingly, we are faced with a methodological dilemma: Shall experiments be designed with the goal of tight experimental control or reflect domain characteristics? Our take on this is that it is important to integrate both perspectives. This might not be possible within one and the same study: Scaling up minimalistic psychology experiments to make them look "natural" is unlikely to add much benefit for application. Conversely, using realistic domain tasks for experimental investigations can render the study of cognitive mechanisms impossible and trivialize the psychological questions that can be asked. Therefore, our suggestion is not to meet in the middle but to combine findings from different types of studies with different levels of complexity. The paradigm-centered research so prevalent in psychology should be complemented by an effort to extract the actual problem structures from specific domains and translate them into mechanistic questions that can be studied in the lab. This endeavor calls for a close cooperation between psychologists and engineers.

Open questions and future studies

The present experiment raises several interesting questions for interdisciplinary research. First, future studies should advance our theoretical understanding of decisions in contexts such as modular plants. For instance, the present results suggest that in ascending sequences people start exploring the Exchange option early on. In other studies, explorative behavior has been found to depend on the history of previous choices and experiences (Cheyette et al., 2016; Hoeffler, Ariely, & West, 2006). These results raise the interesting possibility that the initial quality of options (e.g., Adapt is much better versus much worse) may increase or restrict people's exploration of the other option in subsequent decisions.

Second, the role of interindividual differences should be considered. On the one hand, at present we do not know how Adapt/Exchange decisions depend on experience in the domain. Domain experts do not only differ from novices in terms of knowledge but also in terms of their decision strategies. For instance, some research suggests that there is a trade-off between expertise and flexibility (for a review see Dane, 2010), while other research suggests that experts are in fact more flexible in their choice of situation-specific means (Boulton & Cole, 2016). Obviously, understanding such consequences of expertise is highly relevant for the operation of modular plants. On the other hand, interindividual differences could be assessed to control for the effects of potentially relevant trait variables such as cognitive flexibility, perseveration tendency, self-efficacy, or need for cognition. Understanding whether and how Adapt/Exchange decisions covary with such traits would allow us to assess the convergent and divergent validity of the scenario.

Third, it would be interesting to study the effect of domain-specific factors on the stability-flexibility balance. For instance, time is of major importance in the process industries due to large temporal delays, nonlinear changes, as well as action effects that critically depend on when interventions are made and that can change over time. However, in dynamic decision making studies people tend to focus on options with high immediate payoffs while neglecting long-term benefits (Knox et al., 2012). Therefore, in future studies the short- and long-term consequences of Adapt and Exchange should be pitted against each other.

Fourth, it should be investigated how our findings generalize to other domains. Decisions between modifying the current context versus switching the context are by no means restricted to the operation of modular plants. For instance, a comparable dilemma arises for engineers when designing machines: When is it sufficient to make small modifications to the current solution principle, and when is it necessary to let go of this principle and opt for another one. Design fixation is a major problem in engineering (Alipour, Faizi, Moradi, & Akrami, 2018), and future studies should investigate what aspects of the present work can be generalized to mechanical engineering.

Conclusion

Psychological research on the stability-flexibility balance should not be restricted to closely controlled lab settings but also provide insights into decision making in the real world. To build a bridge between basic and application-inspired psychology, we adopted the problem structure of a real domain and translated it to a relatively simple lab experiment. In this experiment, we studied whether people thoroughly compare options and perseverate on previous choices. The results revealed no evidence for a thorough comparison of options, and instead of sticking with their previous choices, participants flexibly explored Exchange as Adapt became less favorable, but abandoned it as Adapt became possible. These differences to the results from previous psychology studies highlight the importance of extending the problem structures we consider in our experiments.

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