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Brief article

The impact of stimulus uncertainty on attentional control

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ABSTRACT

We argue that stimulus uncertainty induces a cognitive state that can be linked to a concept that has been formerly described as ‘curiosity’ (Berlyne, 1949) – a state that motivates the agent to reduce the uncertainty by exploring it. In two attention filtering tasks we varied response compatibility and stimulus congruency. In addition, we manipulated whether stimulus congruency was predictable or random. In conditions with random presentation the impact of congruency on compatibility was more pronounced suggesting that stimulus congruency was processed more strongly in a random environment. While this makes no sense from a short term strategic perspective in the laboratory, this allocation of attention to uncertain stimulus conditions makes perfect sense outside the laboratory. The impact of uncertainty on attentional control should not be considered a leakage but rather an investment into possible future opportunities.

1. Introduction

The proverb “curiosity killed the cat, but satisfaction brought it back” draws attention to the fact that exploration is risky but necessary to reduce uncertainty. The urge to explore novel situations can be observed in many species and in humans in particular. Berlyne (1949, 1960) attributed these observations to curiosity, a cognitive state that is triggered by uncertainty-inducing stimulus conditions and that motivates the agent to reduce this uncertainty by exploring it.

Uncertainty and uncertainty-reducing mechanisms played a major role in the 1950–70s and have seen a renaissance in recent predictive-coding approaches (Clark, 2013), but with little impact on the study of human attention and the still open question regarding the interplay of exogenous/bottom-up and endogenous/top-down attention (Theeuwes, 2010). While some maintain that information processing is fully controlled by ‘attentional control sets’ (Folk, Remington, & Johnston, 1992), others claim that sufficiently salient task-irrelevant stimuli can capture attention irrespective of attentional goals (Theeuwes, 1992). Awh, Belopolsky, and Theeuwes (2012) suggested giving up the strict opposition of exogenous and endogenous factors and to add the ‘history of selection and reward processes’ as a factor that comprises of both bottom-up and top-down aspects. We agree with this integrative approach but consider the list of relevant factors incomplete without explicit reference to uncertainty.

Uncertainty may be easy to overlook in attentional studies, as participants are provided with information that reduces it – e.g., by

instructions regarding relevant and irrelevant stimuli or stimulus probabilities. Under ecologically more valid conditions, however, uncertainty is likely to be more relevant. Our main claim consists in the assumption that uncertainty draws attention towards the uncertainty-inducing stimulus dimension. This assumption is shared by various theoretical ideas and models, such as Berlyne (1960), Bruce and Tsotsos (2009), Schultz (2000), or Feldman & Friston (2010) — who all claim that attention is drawn most to the source of the greatest uncertainty/surprise.

Here we report two experiments that tested this hypothesis by presenting participants with visual target stimuli that were accompanied (Experiment 1) or preceded (Experiment 2) by irrelevant distractors. Distractors could be target/response compatible or incompatible (Compatibility) and differ or not from the target on a nominally task-irrelevant dimension (color in Experiment 1 or location in Experiment 2; Congruency). Based on previous research, it was expected that Congruency would modulate the compatibility effect: incongruent stimulus displays should lead to smaller compatibility effects since perceptually incongruent distractors are easier to ignore and hence influence responding less while congruent displays should lead to larger compatibility effects since perceptually congruent distractors are harder to ignore and hence influence responding stronger (see Banks & Prinzmetal, 1976; Diedrichsen, Ivry, Cohen & Danziger, 2000; Eriksen & Eriksen, 1979; Zeischka, Coomans, Deroost, Vandenbossche, & Soetens, 2011).

Importantly, the congruency manipulation was either blocked or

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random, assuming that random presentation increases stimulus uncertainty (that is in the random condition there was variance on the congruency-dimension whereas in the blocked condition there was none).¹ We hypothesized, inspired by curiosity predictions of Berlyne (1949, 1960), that greater attention to a particular stimulus dimension should increase the impact that the stimulus sharing this dimension has on selection. Thus, the interaction between Compatibility and Congruency should be more pronounced with random than with blocked presentation (i.e. we expected the three-way interaction of Compatibility \times Congruency \times Presentation). Fig. 1 provides an overview of conditions and results.

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirty-two students from the University of Trier took part in this study in fulfillment of course requirement. One participant was excluded because of high error rates (19.73%). The mean age was 21.9 years (6 male, 18–33 years), all participants reported normal or corrected-to-normal vision. Sample-size was planned for a middle effect size around $d_z \sim 0.5$ based on previous research on flanker effects and aiming for a power of $1 - \beta > 0.80$ (calculations were run with G-Power 3.1; Faul, Erdfelder, Buchner, & Lang, 2009).

2.1.2. Stimuli and apparatus

The experiment was conducted in sound-protected testing booths. Instructions and stimuli were presented on a standard 22-inch color monitor (1680 \times 1050 pixels) and a refresh rate of 60 Hz. The instructions were presented in white on black background, and the distance between participant and monitor was approximately 60 cm. Responses were measured with a standard PC mouse. The experiment was created with E-Prime software (version 2.0). The letters D, F, J and K (font: Courier New) served as flankers and targets. Letters were approximately 0.85° in height and 0.85° in width. A row of five letters appeared in each trial, a central target with two identical flankers on the left and right side. The target did not appear exactly at screen center but was shifted 4% (1.9 cm, 1.84°) to the left or right from the center to make spatial selection harder. Letters in the practice phase appeared in white (CIE L* a* b-value: 100, 0, 0), in the experimental trials they appeared in red (CIE L* a* b-value: 53, 80, 67), or lime (CIE L* a* b-value: 88, -86, 83).

2.1.3. Procedure

Participants were instructed to respond as rapidly and as correctly as possible to the middle letter of the string. The letters D and F were mapped to one mouse-key and the letters J and K to the other, the stimulus-response mapping was counterbalanced across participants. In 50% of all trials, the incompatible trials, the flankers and the target indicated different responses. In the other 50%, the compatible trials, the target and the flankers indicated the same response. In 50% of all compatible trials, target and flankers were identical (e.g., target F and flankers F) and in the other 50%, target and flankers were different (e.g., target F and flankers D).

Each trial was initiated by 300-ms blank interval and a plus sign serving as fixation mark presented for 400 ms at screen center. After a blank interval of 600 ms, the target-flanker string appeared for 200 ms, followed by another blank interval until the response was given or

1000 ms had passed. Participants could respond to the target with the onset of the flanker display. The target always appeared in lime. Flankers also appeared in lime (congruent condition) in 50% of all trials and in red (incongruent condition) in the other 50%. In the blocked-presentation condition, all 128 trials of the congruent condition were presented in one block and all 128 trials of the incongruent condition in another. In the random-presentation condition, congruent and incongruent trials were randomly intermixed in two 128-trial blocks. Block sequence was counterbalanced across participants.

Participants began by performing two training blocks with error feedback. In the first (24-trial) block, participants were presented only with the target to learn the stimulus-response mapping. In the second (64-trial) block, both targets and flankers presented in white. Each experimental block started with 24 warmup trials (that were not further analyzed) and then proceeded with the 128 experimental trials. Overall, participants performed 512 experimental trials, and breaks were offered every 40 trials. If the program detected incorrect or missing responses in three consecutive trials, an additional break was recommended.

2.1.4. Analysis

Here we consider only trials in which flankers and targets were either identical or response-incompatible—the most common conditions in flanker experiments and to make Experiment 1 more comparable to Experiment 2; for more elaborate analyses including also sequential analyses see the [online supplement](#). Note that neither Compatibility nor Congruency sequential effects did influence the main result reported below (that is the three-way interaction between Compatibility \times Congruency \times Presentation) and that the pattern still holds if all trials are included. Reaction times (RTs) from correct trials, after excluding those with RTs shorter than 200 ms or longer than 1.5 interquartile ranges above the 3rd quartile of each participant's individual RT distribution (Tukey, 1977), and error rates (ERs) were analyzed with a $2 \times 2 \times 2$ factorial design, with the three within-participants factors of flanker *Compatibility* (identical vs. incompatible), *Congruency* (congruent vs. incongruent) and *Presentation* (blocked vs. random).

2.2. Results

In RTs, a MANOVA with Pillai's trace as criterion yielded significant main effects of Compatibility, $F(1, 30) = 490.84, p < .001, \eta_p^2 = 0.94$, with faster RTs for compatible (574 ms) than for incompatible trials (636 ms), and Congruency, $F(1, 30) = 101.61, p < .001, \eta_p^2 = 0.77$, with faster RTs in the incongruent (588 ms) than in the congruent condition (622 ms), while the main effect of Presentation was not significant, $F < 1$. The interactions of Compatibility and Congruency, $F(1, 30) = 53.96, p < .001, \eta_p^2 = 0.64$, and of Congruency and Presentation, $F(1, 30) = 6.89, p = .014, \eta_p^2 = 0.19$, were further moderated by a significant three-way interaction, $F(1, 30) = 6.42, p = .017, \eta_p^2 = 0.18$. As Fig. 1 shows, the compatibility effect was smaller in the incongruent than in the congruent condition, and this interaction was more pronounced with random than with blocked presentation.

In ERs, the same analysis revealed significant main effects of Compatibility, $F(1, 30) = 19.23, p < .001, \eta_p^2 = 0.39$, with fewer errors in compatible (4.13%) than in incompatible trials (6.36%), and Congruency, $F(1, 30) = 11.21, p = .002, \eta_p^2 = 0.27$, with fewer errors in the incongruent (4.20%) than in the congruent condition (6.30%). The three-way interaction was not significant, $F(1, 30) = 0.02, p = .889, \eta_p^2 = 0.00$, the interaction of Compatibility and Presentation was, $F(1, 30) = 8.01, p = .008, \eta_p^2 = 0.21$, indicating a stronger compatibility effect in the blocked (3.33%) than the random condition (1.13%).

¹ Note, that in conditions in which Congruency was blocked the amount of compatible and incompatible trials was exactly the same as compared to conditions in which Congruency was random (in other words our approach does not investigate compatibility-proportion manipulations; e.g., Risko, Blais, Stolz, & Besner, 2008).

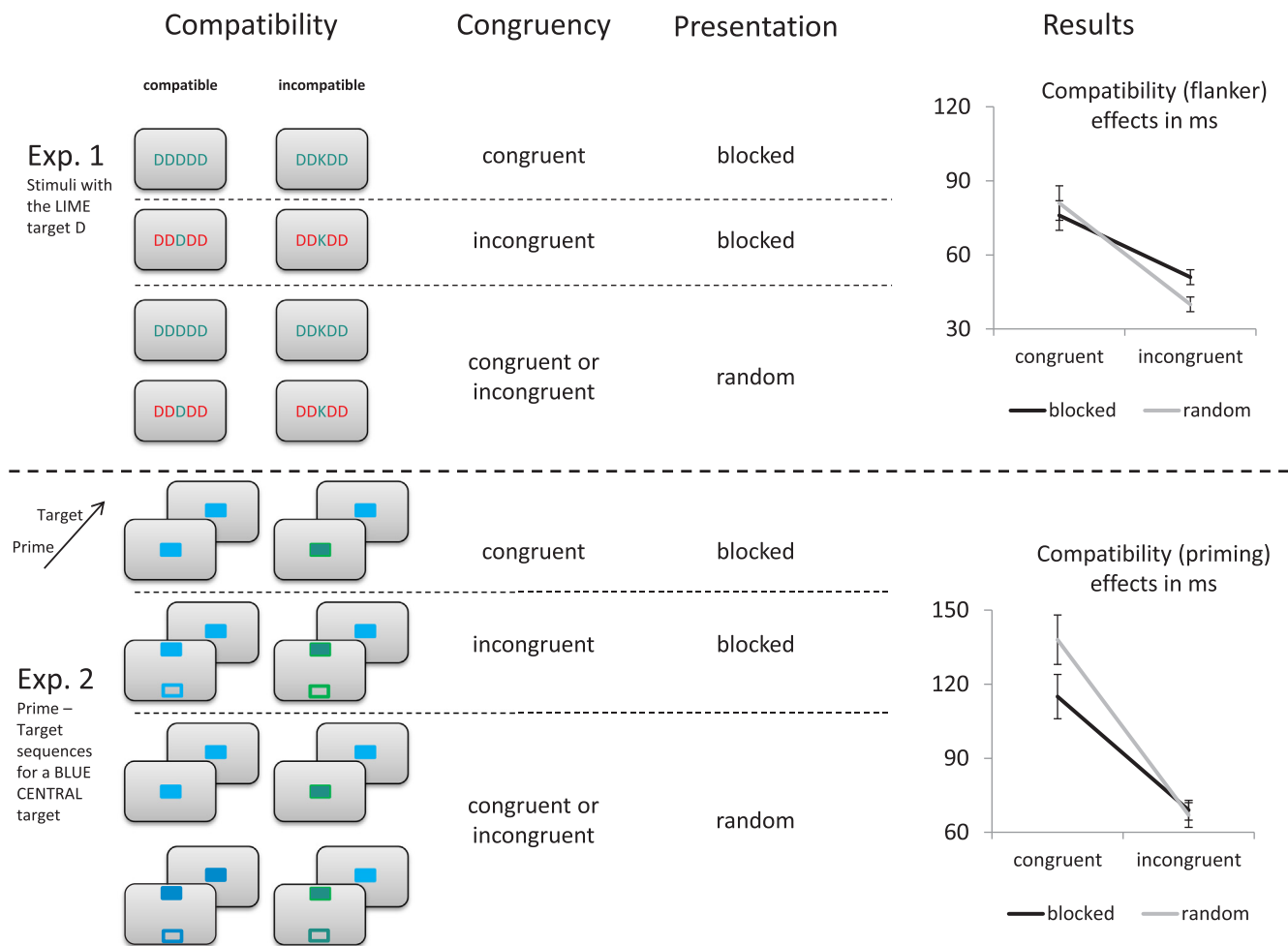


Fig. 1. Overview of stimulus conditions (stimuli not drawn to scale) and results of Experiments 1 and 2. Note that Congruency concerns color-congruency in Experiment 1 and location-congruency in Experiment 2 (in Experiment 2 in incongruent conditions, the prime appeared either above or below the central target location – depicted here as a full and an empty prime-rectangle). Participants classified the central letter in Experiment 1, and the color of the central rectangle on the target-display in Experiment 2. In blocked conditions, all trials were either congruent or incongruent while in random conditions congruency varied randomly from trial to trial (see text for a detailed explanation). Results depict mean Compatibility effects (flanker effects in Experiment 1, response priming effects in Experiment 2) with SEs.

3. Experiment 2

3.1. Method

3.1.1. Participants

Thirty-two new psychology students participated. The data of two participants were discarded due to extremely high ER (35.94% and 31.64%). For the analyzed data, the mean age was 21.00 years (3 male, 17–27 years) and they fulfilled the same criteria as in Experiment 1. Sample-size was planned for a middle effect size around $d_z \sim 0.5$ based on previous research on congruency modulations on response priming effects and aiming for a power of $1 - \beta > 0.80$ (calculations were run with G-Power 3.1; Faul et al., 2009).

3.1.2. Stimuli and apparatus

These were as in Experiment 1, except that green (CIE L*a*b-value: 46, -52, 50) and blue (CIE L*a*b-value: 32, 79, -108) $1.49^\circ \times 1.72^\circ$ rectangles served as distractors and targets. The target always appeared at screen center while the distractors were presented at either the same central location (congruent condition) or 3.8° above and below (incongruent condition).

3.1.3. Procedure

Two stimuli appeared on two consecutive displays, and participants were instructed to ignore the first (prime display) and respond as rapidly and as correctly as possible to the color of the second (target display). The identities of distractor and target were uncorrelated. In 50% of all trials, the incompatible trials, distractor and target indicated different responses. In the other 50%, the compatible trials, distractor and target indicated the same response.

Each trial was initiated by a 300-ms blank interval followed by a central plus sign appearing for 500 ms and the distractor, which appeared for 30 ms. The time between the onset of the distractor and the onset of the 30-ms target varied randomly between 80 and 160 ms, in 40-ms steps. Once the target disappeared, participants had to respond within the next 1000 ms. The central target appeared in blue or green to signal the left or right mouse click. The distractor appeared in either the same color as the target (compatible condition) or in the opposite color (incompatible condition). Distractors appeared in either the same central location as the target (congruent condition) or above and below (incongruent condition). In the blocked-presentation condition, all 192 trials of the congruent condition were presented in one block and all 192 trials of the incongruent condition in another. In the random-presentation condition, congruent and incongruent trials were randomly intermixed in two 192-trial blocks. Block sequence was

counterbalanced across participants.

Participants began by performing 48 practice trials without distractor presentation and with error feedback. Each experimental block started with 16 warmup trials (that were not further analyzed) and then proceeded with the 192 experimental trials. Overall, participants performed 768 experimental trials, and breaks were offered every 40 trials. If the program detected incorrect or missing responses in three consecutive trials, an additional break was recommended.

3.2. Results

The data were treated as in Experiment 1. For sequential analyses see the [online supplement](#). In RTs, we obtained significant main effects of Compatibility, $F(1, 29) = 358.40$, $p < .001$, $\eta_p^2 = 0.93$, with faster responses for compatible (436 ms) than for incompatible trials (534 ms), Congruency, $F(1, 29) = 59.13$, $p < .001$, $\eta_p^2 = 0.67$, with faster responses for incongruent (469 ms) than congruent trials (500 ms), and Presentation, $F(1, 29) = 19.36$, $p < .001$, $\eta_p^2 = 0.40$, with faster response for the blocked (475 ms) than the random condition (495 ms). The interactions of Compatibility and Congruency, $F(1, 29) = 132.27$, $p < .001$, $\eta_p^2 = 0.82$, and of Compatibility and Presentation, $F(1, 29) = 5.08$, $p = .032$, $\eta_p^2 = 0.15$, were also significant, as was the three-way interaction, $F(1, 29) = 13.78$, $p = .001$, $\eta_p^2 = 0.32$. As [Fig. 1](#) shows, the compatibility effect was smaller in the incongruent than in the congruent condition, and this interaction was more pronounced with random than with blocked presentation.

The ER analysis yielded significant main effects of Compatibility, $F(1, 29) = 81.00$, $p < .001$, $\eta_p^2 = 0.74$, with fewer errors in compatible (2.44%) than incompatible trials (11.42%), and Congruency, $F(1, 29) = 15.57$, $p = .001$, $\eta_p^2 = 0.35$, with fewer errors in incongruent (5.16%) than congruent trials (8.70%). The interactions of Compatibility and Congruency, $F(1, 29) = 13.62$, $p = .001$, $\eta_p^2 = 0.32$, and of Congruency and Presentation, $F(1, 29) = 4.17$, $p = .050$, $\eta_p^2 = 0.13$, were also significant, while the three-way interaction approached significance, $F(1, 29) = 3.40$, $p = .075$, $\eta_p^2 = 0.11$: the compatibility effect was smaller in the incongruent than in the congruent condition, and this interaction tended to be more pronounced with random than with blocked presentation.

4. Conclusions

We tested the hypothesis that uncertainty automatically attracts attention – i.e. whether uncertainty with respect to a task-irrelevant stimulus dimension attracts attention to this dimension. The main prediction was a three-way interaction: increasing uncertainty should boost the impact of distractor-target congruency on response-compatibility effects (i.e. the two-way interaction of Congruency \times Compatibility that was expected based on previous studies should be modulated by Presentation condition). This expectation was fully met in both experiments (the three-way interaction was significant in the RTs in Experiment 1 and 2, and approached significance in the error rates in Experiment 2), suggesting that uncertainty (here variance in a task-irrelevant dimension) boosts the impact this dimension has on attentional selection (see the [online supplement](#) for a somewhat different interpretation).

On the one hand, this fits with the general claim of [Awh et al. \(2012\)](#) that the stimulus-related history is an important factor in attentional control: stimulus uncertainty reflects both the relative frequency with which a particular stimulus has appeared under particular circumstances in the past and the number of alternatives that occurred or could have occurred under these circumstances ([Berlyne, 1960](#)). On the other hand, uncertainty does not seem to fit under the general umbrella of selection and reward history, which renders the account of [Awh et al.](#) incomplete.

The observation that uncertainty affects attentional control underscores the human brain's key function to optimally predict, and prepare

the agent for future events ([Friston, 2009](#); [Sokolov, 1963](#)). Prediction relies on past experience and uncertainty reduction, so that an adaptive attentional system should indeed direct processing to not-yet-sufficiently-well predicted stimulus events or aspects thereof. While this might not be strictly necessary for laboratory tasks, it provides the database needed for a reliable representation of the experienced events. The fact that these representations seem to go beyond present minimal requirements may seem uneconomical ([Mast & Frings, 2014](#)). Yet, if we consider that truly adaptive behavior should not only rely on persistence on the current task but also to some degree rely on flexibility in considering available alternatives that one may want to switch to ([Hommel, 2015](#)), a richer-than-necessary representation of current events makes perfect sense. From that perspective, the impact of uncertainty on attentional control should not be considered a leakage but rather an investment into possible future opportunities.

CRedit authorship contribution statement

Christian Frings: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. **Simon Merz:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software Writing - original draft. **Bernhard Hommel:** Conceptualization, Visualization, Writing - original draft, Writing - review & editing.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <http://dx.doi.org/10.23668/psycharchives.923>.

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