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Disentangling semantic and response learning effects in color-word contingency learning

Sebastian Geukes[1,2], **Dirk Vorberg**[1,2], **Pienie Zwitserlood**[1,2]*

1 Institute of Psychology, Westfälische Wilhelms-Universität Münster, Münster, Germany, **2** Otto-Creutzfeldt-Center for Cognitive and Behavioral Neuroscience, Westfälische Wilhelms-Universität Münster, Münster, Germany

* zwitser@uni-muenster.de

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Abstract

It is easier to indicate the ink color of a color-neutral noun when it is presented in the color in which it has frequently been shown before, relative to print colors in which it has been shown less often. This phenomenon is known as color-word contingency learning. It remains unclear whether participants actually learn semantic (word-color) associations and/or response (word-button) associations. We present a novel variant of the paradigm that can disentangle semantic and response learning, because word-color and word-button associations are manipulated independently. In four experiments, each involving four daily sessions, pseudowords—such as *enas*, *fatu* or *imot*—were probabilistically associated with either a particular color, a particular response-button position, or both. Neutral trials without color-pseudoword association were also included, and participants' awareness of the contingencies was manipulated. The data showed no influence of explicit contingency awareness, but clear evidence both for response learning and for semantic learning, with effects emerging swiftly. Deeper processing of color information, with color words presented in black instead of color patches to indicate response-button positions, resulted in stronger effects, both for semantic and response learning. Our data add a crucial piece of evidence lacking so far in color-word contingency learning studies: Semantic learning effectively takes place even when associations are learned in an incidental way.

Introduction

Children learning their first language, and adults learning a foreign language, are trying to establish reliable connections between words and the meanings they refer to. Learning word-concept relations is thus one of the core challenges associated with mastering a novel language, and by now there is ample evidence that such learning can be fast and efficient [1, 2, 3, 4].

In real life, information about potential word-concept relations is often ambiguous. To mimic this, many studies have employed a statistical learning approach: Novel words and their concepts are paired in a probabilistic manner, and learners must infer the correct word-concept relations over the course of the learning phase [5, 6, 7, 8, 9, 10, 11]. For example, Breitenstein et al. [5] presented their participants with stimulus pairs consisting of an object picture and a spoken novel word (which were pseudowords in the participants' native language). A particular novel word (e.g., *binu*) was paired with a particular object picture (e.g., a dog) half of the time (the to-be-learned combination of novel word and meaning); in the other half, the novel word was combined with many different objects. As expected, telling apart correct from incorrect pairs–the task during learning—took time, but participants successfully learned to associate the semantics of concepts with correct novel words, as they could easily tell apart correct from incorrect pairs. Crucially, novel words (e.g., *binu*) effectively primed semantically related stimuli (e.g., picture of a cat), showing that they were indeed tightly connected to the conceptual semantic network.

Color concepts provide an interesting semantic field to study the association of novel words to existing meaning. Given that the conceptual space is small, it provides an ideal testing ground. Surprisingly, it has not been used very often (but see [12, 13, 14]). In a previous study, we employed the statistical word-learning paradigm to test the association of novel words to color concepts. Effects of learning were assessed in terms of congruency effects in the manual Stroop task, in which the colors are identified by means of a key press [8]. Novel words that had been associated with native-language color words (e.g., *binu* associated with the word *red*) led to sizeable Stroop congruency effects on color-matching speed. This novel-word Stroop effect arose under two conditions: (1) immediately after learning, but only when novel words and native-language color words were present in the same Stroop blocks, or (2) with and without native-language color words, when tested 24 hours after learning, providing an opportunity for memory consolidation. The Stroop congruency effect for novel pseudowords was smaller than, but similar to, the native-language Stroop effect.

Crucially, we had to make sure in this experiment that no further learning of the correct pair took place within the Stroop task. In fact, there is reliable evidence that the congruency effect in the manual Stroop task is partially due to word-response associations learned during the experiment itself ([15, 16] with color naming). This is because, in the typical four-color Stroop experiment with 50% congruent and 50% incongruent trials, each color word appears three times as often in its congruent print color as in either of the three incongruent print colors [17, 18]. This allows participants to learn direct word-to-response associations, which speeds up manual reactions on congruent trials. The relevance of this type of contingency learning is seen best when color-unrelated words (e.g., *move*, *wide*, *rest*) are used instead of color words. This has been done in a paradigm called color-word contingency learning [19, 20, 13]. In the manual variant of the Stroop task, the print color of stimulus words is indicated by pushing the color-matching response button. There were two crucial differences to the classic version with native-language color words: (1) color-unrelated words (e.g., *month*) were used, rather than color words (e.g., *red*), and (2) these words were presented more often in one print color (e.g., 75% in red) than in any of the other colors. These experiments showed that participants do indeed adapt to arbitrary word-color contingencies, as evidenced by faster responses to words presented in their frequent color than in any of the other colors ([19, 21, 22, 23] for the influence of processing speed on color-word contingency learning). These adaptation effects arise after just a few learning trials, remain stable in size, and are unlearned and re-learned rapidly [21, 22].

While adaptation effects to presentation frequencies are clear-cut, their explanation is not. At least two possibilities come to mind: (i) According to the *word-concept* (or semantic) learning hypothesis, congruency effects arise because words (novel and color-neutral existing words alike) become associated with color concepts, which facilitates selection of the correctly colored response button; (ii) According to the *word-response* learning hypothesis, congruency effects arise because the word is probabilistically paired with one particular *response* (the one for the word's most frequent color), such that participants become faster over time to select the correct manual response to a given word. Thus, it is valid to attribute congruency effects in color-word contingency learning to semantic associations only if such effects do indeed arise via word-concept learning. One way to distinguish semantic from response learning is to map the four colors typically used in color-word contingency learning onto two (neutrally colored) response buttons. In this setup, each button represents two colors (e.g., "if the word's print color is either blue or yellow, press the left button"). This was realized in Experiment 4 of Schmidt et al. [19], in which the authors distinguished between three types of trials:

- **response mismatch**, when neither the print color nor the required response is the one most frequently associated with the presented word;
- **response match**, when the response but not the print color is associated with the word;
- **stimulus match**, when both print color and response are associated with the presented word.

These conditions permit distinguishing two separate learning components from each other: If there is response learning, responses should be faster on response match than on response mismatch trials. This is so because the word in the response match condition, while printed in a non-contingent color, nevertheless points to its correct response, thereby facilitating response selection. If there is semantic learning, however, responding should be faster on stimulus match than on response match trials. This is because the congruency between word and print color may facilitate the selection of the correct response over and above word-response congruency.

Schmidt and colleagues [19] found evidence for response learning (a 26 ms effect), but no reliable advantage for stimulus-match over response-match trials (a net difference of 2 ms). Their conclusion was that color-word contingency learning reflects response learning only, not semantic learning. This is different from the classic manual Stroop task with native-language color words and a two-on-one response mapping, where both semantic and response congruency effects are reliably observed [15, 24, 25, 26].

While certainly informative, the 2:1 mapping task design has drawbacks. For example, while response options are reduced to two responses, there are still four colors to be distinguished, which could facilitate the learning of response contingencies via color contingencies. Also, words are always correlated with both color and response. Consequently, semantic and response learning are neither learned nor tested independently–for example, by using separate sets of words. It is conceivable that participants do in fact learn semantic contingencies, which need not show up in response times if the response contingency dominates any semantic (word-color) contingency effect. Semantic contingencies might lead to measurable effects, either (i) when learned independently of response-position contingencies, or (ii) when tested in different semantic paradigms. Thus, while the 2:1 mapping design does offer some evidence for dominant response-learning effects, this does not necessarily imply that participants fail to learn word semantics as well (see [27] for stimulus-independent category learning with color-word contingencies; [28] for evaluative contingency learning). A more general factor that might hamper semantic learning in the above studies is the fact that the words possessed meaning. Exactly because "move" or "rest" are not associated with a particular color–a prerequisite for their choice as stimuli–adding color to their semantic representation may be quite difficult to learn.

The goal of the current study was to separate semantic from response components in color-word contingency learning, by independently manipulating word-color and word-response

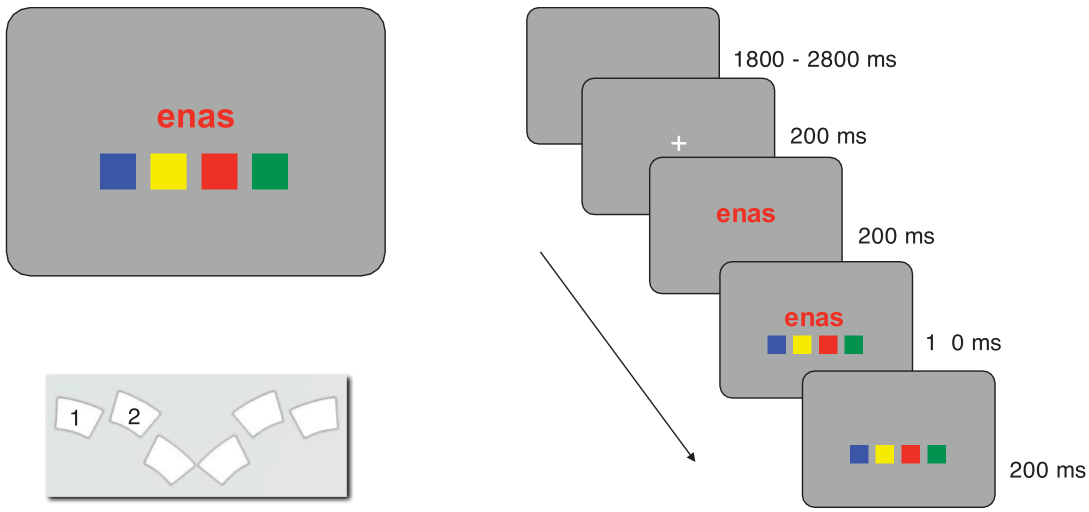

Fig 1. Stimulus display, spatial arrangement of response buttons, and trial timing. Panel A shows the typical stimulus display and response button layout in Experiments 1, 2, and 4. Panel B illustrates a typical trial. Numbers in Panel A schematically indicate which buttons of the response box were used in the experiments; actually, buttons were not labelled. The same timing of stimulus elements applied in all four experiments.

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associations across separate sets of pseudowords. To do so, we introduced a variant of the color-matching Stroop task in which the print color of pseudowords is to be reported via button presses, as in previous color-word contingency studies. We used two-syllable pseudowords (e.g., *ugir*, *inwa*) which, by definition, are not associated with any color, as they have no established referential meaning at all. The key difference from previous studies is the following: Simultaneously with the colored pseudoword, four color squares (Experiments 1, 2, and 4) are presented. The participants' task is to indicate by button press which of the squares matches the pseudoword's print color (see Fig 1A). Note that our task differs from the standard Stroop matching task, which is essentially a Yes-No (match/mismatch) procedure. The task allows us to vary the association of colors (red, green, blue, or yellow) to response positions (button 1, 2, 3, or 4) on a trial-by-trial basis, and thus permit us to separately manipulate pseudoword-color and pseudoword-position contingencies. In Experiment 1, 2, and 3, the assignment of a particular pseudoword to a particular contingency was held constant throughout; in Experiment 4, this assignment was re-randomized from block to block. In Experiment 3, we replaced the colored squares by color words printed in black, which surrounded the colored pseudoword.

We used this paradigm in four experiments, to separate semantic from response learning effects in color-word contingency learning. Contingency type was blocked, with particular pseudowords associated either with color (Col), with spatial response position (Pos), or with both (ColPos). In a fourth contingency type, pseudowords were correlated with both color and response position, while the spatial order of the color patches was held constant throughout the experiment (ColPosFix), which closely resembles experiments with a spatially fixed set of colored response buttons. A neutral condition (an additional pseudoword for which color and/or position varied randomly) was used in each of the four contingency conditions, to assess interference and facilitation [16, 21]. Each experiment comprised four daily sessions, with two blocks of each contingency type in each session. The particular contingencies were determined randomly for individual participants but were kept constant throughout their experiment.

In Experiment 1, we tested whether the color-pseudoword contingencies do in fact induce congruency effects, and, if so, how they depend on contingency conditions. In Experiment 2, we tested whether knowledge of the type of contingency present in the upcoming block changes the pattern of effects, as previous evidence suggests that explicit contingency awareness affects the size of effects [29]. In Experiment 3, we used color words (printed in black) rather than color patches as response cues to indicate the current trial's response mapping. Color-to-color mapping was thus not possible in this experiment; colors had to be identified and matched to their names. Experiment 4 tested how rapidly contingency effects arise, by varying color-pseudoword contingencies from block to block, rather than keeping them constant across blocks.

Our predictions were as follows. We expected congruency effects in the ColPosFix condition that is closest to the standard version of color-word contingency with fixed, colored response buttons [19, 21]. We also predicted congruency effects in the condition that combines position and color information (ColPos). If color-word contingency learning reflects response learning, as Schmidt and colleagues claim, we predicted small but reliable congruency effects when only position information is present (Pos). Finally, we also expected evidence for semantic learning with color information in the absence of position information, because such information can become associated with novel words if cues are sufficiently consistent (Geukes et al., 2015). However, the effects should be smaller than with fixed spatial arrangement of the colored response cues, given that 'position habits' are easily formed in learning, as suggested by findings in animal discrimination learning (e.g., [30]).

Experiment 1

Method

Participants. Ten students (7 female; age: $M = 23.50$, $SD = 3.14$) took part, in four sessions on consecutive days. All had normal or corrected-to-normal visual acuity and normal color vision, as assessed by standard Ishihara plates. Participants gave written consent and received either course credit or 25 € compensation. All procedures were approved by the Ethics committee of the Department of Psychology, University of Münster.

Word materials. Twenty bi-syllabic pseudowords were used as stimuli (*ahak*, *alep*, *edok*, *emgu*, *enas*, *fatu*, *fepa*, *imot*, *inwa*, *kela*, *kopu*, *meha*, *mupa*, *palo*, *osig*, *ovon*, *sego*, *tihe*, *ugir*, *utaf*). They were selected from the materials developed and empirically validated by Breitenstein and Knecht [6], who have shown that these pseudowords elicit few associations to existing German words and are of neutral emotional valence. On each trial, a single pseudoword, uniformly colored, was presented centered on a grey screen (see Fig 1), printed in red, green, blue, or yellow. RGB values: red (255, 0, 0), green (0, 255, 0), blue (255, 255, 0), yellow (0, 0, 255), grey (35, 35, 35).

Color matching task. A colored pseudoword (in red, green, blue, or yellow) appeared in the screen center, above a row of four differently colored squares, one of which always matched the pseudoword's print color (see Fig 1A). The task was to locate the color-matching square, and to push the button corresponding to its position on the response box as quickly as possible. Depending on experimental conditions, the spatial arrangement of the color squares on the screen either varied from trial to trial or was constant within a block (see below).

Contingency conditions. There were four contingency types. In 80% of the cases, a pseudoword either appeared (a) in one and the same print color (but at different positions; Col), (b) was associated with the same spatial response position (but varied in color; Pos), (c) had the same color and response position (ColPos), or (d) had the same color and response position, with a constant spatial order of the response cues within the block (ColPosFix).

For each participant, the 20 pseudowords were randomly partitioned into four subsets of five pseudowords each, and each subset was assigned to one of four contingency conditions. In each subset, one of the five pseudowords served as control, with print color and position of the matching color patch chosen randomly on any trial. The other four pseudowords were assigned to a contingency condition. For example, in a *Col*-contingency block, each of the four pseudowords was presented on 15 trials altogether, on 12 trials (p = .8) in its assigned color ('congruent', e.g., *blue*), and on 3 trials (1—p = .2) in either one of the remaining three colors ('incongruent', e.g. *red*, *green*, or *yellow*). The same principle was used in Pos, ColPos, and ColPosFix blocks: *Pos*-words were assigned to one of the four response positions. They could appear in any color, but the correct response, that is, the spatial position of the matching color patch, was predictable (p = .8). Analogously, for ColPos-*words* and for ColPosFix-*words*, both color and response position were predictable (the latter with a fixed color-to-button assignment, see below).

Experimental conditions. The experiment followed a 4 x 3 x 8 experimental design: Contingency Type (Col, Pos, ColPos, ColPosFix) x Congruency (congruent, incongruent, neutral) x Block Repetition (1 to 8). Within each block of 75 trials, a fixed subset of five pseudowords was used: one neutral–uncorrelated—control pseudoword and four experimental pseudowords of the same type (either Col, Pos, ColPos, or ColPosFix). Each pseudoword appeared as colored stimulus on 15 trials per block. For experimental pseudowords, color and/or position of the matching color patch were consistent on 12 trials and inconsistent on 3 trials within each block. For neutral pseudowords, color and response position of the matching color patch varied randomly from trial to trial. As stated above, ColPos-pseudowords and ColPosFix-pseudowords were associated both with a color and a response position. ColPos-blocks and ColPosFix-blocks were constructed identically, except for the spatial arrangement of the color patches on the screen (see Fig 2). In ColPos-blocks, the three incorrect color patches appeared randomly at the remaining positions. in ColPosFix-blocks, the color patches were presented in a fixed spatial order throughout the entire block, analogous to a physically fixed arrangement of color-labelled response buttons.

Trial events and task. Stimuli were presented on an LCD color monitor (*Samsung 2233 RZ*, *120 Hz*, *22 inch*) using the *Presentation* software package (*Neurobehavioral Systems*, *Inc*.). Each trial started with a fixation mark, followed by a colored stimulus pseudoword and the four color patches. The exact timing of stimulus events is shown in Fig 1B.

Participants were to press the response button that spatially corresponded to the location of the color patch that matched the pseudoword's color. (Response box: *RB-830*, *Cedrus Corp*., *San Pedro*, *CA*; see Fig 1A for the button layout). To make the particular contingencies less obvious and to avoid associations of specific visual stimuli to color and/or position, we randomly varied font type (8 styles) and font size (4 sizes) of the pseudowords from trial to trial (cf. [31]). Thus, each pseudoword could appear in any one of 32 different forms.

Response times were measured from pseudoword onset. Incorrect responses or response omissions (response time > 2000 ms) were signaled by a low or high pitch tone, respectively, delivered via headphones. The timing of this feedback depended on the participant's response latency.

Before the first main block, participants were given two practice blocks of 40 trials each. Each participant took part in four daily 1-h sessions, each of which contained eight contingency blocks with 75 trials. Blocks 1–4,and 5–8 contained each contingency type (Col, Pos, ColPos, ColPosFix); their order was random. Thus, each contingency type occurred twice per session, eight times overall. For each participant, individual assignments of pseudowords to particular within- and between-block contingency types applied throughout the whole experiment. In all, each participant responded on 2400 trials (384 incongruent trials, 384 congruent trials of each of the four contingency types, in addition to 480 neutral trials).

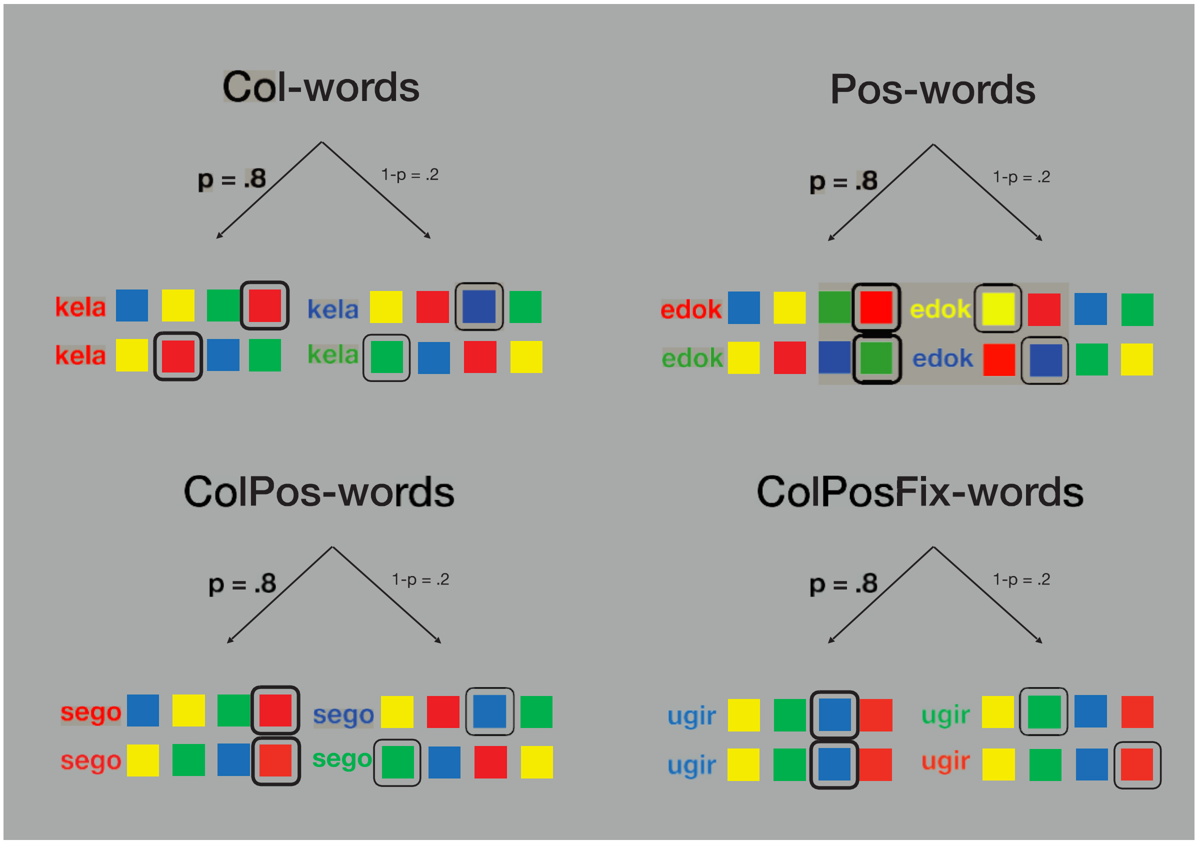

Fig 2. Four contingency types. Pseudowords were associated with color and/or response position in the Stroop task, yielding congruent (p = .8) and incongruent (1–p = .2) trials (p denotes the probability of a congruent trial for a given pseudoword). Two example trials are shown for each contingency condition. Note that for ColPosFix trials only, the spatial order of the color squares remained fixed throughout.

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Performance feedback (mean response time, percentage correct) was provided after each block. There was an obligatory 5-minute rest after block 4. Participants were encouraged to take rests between blocks if needed. Apart from the mid-session break, they started blocks at their discretion. No information was provided about the task structure and its changes across trial blocks.

Analysis. For the response-time analyses, trials with RTs below 100 ms (less than 0.1% of all responses) were excluded, as well as error trials. For the remaining correct response trials, trimmed response-time means (5% trim at each distribution end, see [32] for this procedure) were calculated per participant and Contingency type (Col, Pos, ColPos, ColPosFix), Congruency (congruent, incongruent, neutral) and Block Repetition (1 to 8). Error rates were similarly calculated per experimental cell and subsequently arcsine square-root transformed for the analysis of variance (ANOVA). Trimmed response-time means and transformed error rates were both analyzed by repeated-measures ANOVA.

Awareness of contingencies. Following the final session, participants were handed a stack of cards each of which contained one of the 20 pseudowords printed in black. In two separate matching trials, participants were to match each pseudoword as best as possible both to (a) one of the four colors and (b) to one of the response positions. For this purpose, sheets were provided with four columns labelled either for the four colors or for the four response positions.

We determined the number of correct matches for the experimental pseudowords of each contingency type (Col, Pos, ColPos, ColPosFix), separately for color and for position contingency. For each contingency type, participants could correctly match between 0 and 4 pseudowords. Whether matching was better than chance (25%) was tested by one-sided one-sample t-tests. Considering the problems associated with confirming the null hypothesis in Null-Hypothesis Significance Testing, we also calculated JZS Bayes factors, assuming a standard Cauchy prior with r equal 0.707, using the *JASP software package* [33].

Results

Mean response times from Experiment 1 are shown in Fig 3A. Because the overall range of response times was large and there were considerable practice effects across sessions, the experimental effects of main interest are hard to discern from the absolute response times. Therefore, we include additional graphs of the net effects that show the differences between experimental conditions (Fig 3B).

Results from Experiment 1 showed a small but reliable difference of, on average, 12 ms between the congruent and incongruent conditions (henceforth called Congruency effect). This effect emerged early and remained relatively stable throughout the eight blocks. Response times to neutral pseudowords were in between those in congruent and incongruent conditions, suggesting the presence of both facilitation and interference. The ANOVA on response times revealed significant main effects of Block Repetition, Contingency Type, and Congruency, but no reliable interactions. The Congruency main effect, $F(2, 18) = 24.04$, $p < .001$, was driven by faster responses on congruent (557 ms) than on neutral trials (566 ms), $t(9) = 4.44$, $p = .002$, which in turn were faster than those on incongruent trials (569 ms), $t(9) = 3.04$, $p = .013$. Response times also differed between Contingency Types, $F(3, 27) = 46.09$, $p < .001$; responses were slowest in Pos-blocks (593 ms), followed by Col-blocks (586 ms), ColPos-blocks (547 ms) and ColPosFix- blocks (530 ms). All differences between Contingency Type mean response times were significant with $t(9) \geq 3.69$, $p \leq .005$. Finally, response speed improved with Block Repetition, $F(7, 63) = 10.92$, $p < .001$, decreasing from 591 ms to 549 ms over the eight blocks.

Of the interactions, the Congruency × Contingency *Type* interaction just failed significance, $F(6, 54) = 2.09$, $p = .069$. We nevertheless conducted follow-up comparisons to test our predictions for the four contingency types. The response-time difference between congruent and incongruent trials failed significance in the Col-condition (4 ms, $t(9) = 1.33$, $p = 0.216$), but was significant in the three conditions with position contingencies (Pos: 14 ms, $t(9) = 2.80$, $p = 0.021$; ColPos: 15 ms, $t(9) = 4.35$, $p = 0.002$; ColPosFix: 15 ms, $t(9) = 8.57$, $p < .001$). None of the remaining interactions turned out reliable (Block × Contingency type: $F(21, 189) = 1.32$, $p = .160$; Congruency × Block Repetition: $F(14, 126) = 0.93$, $p = .532$; Congruency × Block Repetition × Contingency Type, $F(42, 378) = 0.91$, $p = .638$).

Error rates were low, around 3%, and their pattern across congruency conditions was roughly consistent with the pattern in response times (congruent: 2.7%, neutral: 3.1%, incongruent: 3.1%; see Figure A in S1 File). The ANOVA of the (arcsine transformed) error rates yielded a marginal main effect of Congruency, $F(2, 18) = 3.50$, $p = .052$. This congruency pattern was present in all blocks with position contingencies (Pos: congruent 2.7%, incongruent 4.2%; ColPos: congruent 2.4%, incongruent 3.1%; ColPosFix: congruent 2.2%, incongruent 2.8%), but it was reversed in the Col-condition (congruent 3.3%, incongruent 2.3%). There was also a marginal three-way interaction of Congruency, Block Repetition, and Contingency Type, $F(42, 378) = 1.42$, $p = .050$. No other interactions or main effects were statistically reliable (all Fs < 1.86, all $p > .105$).

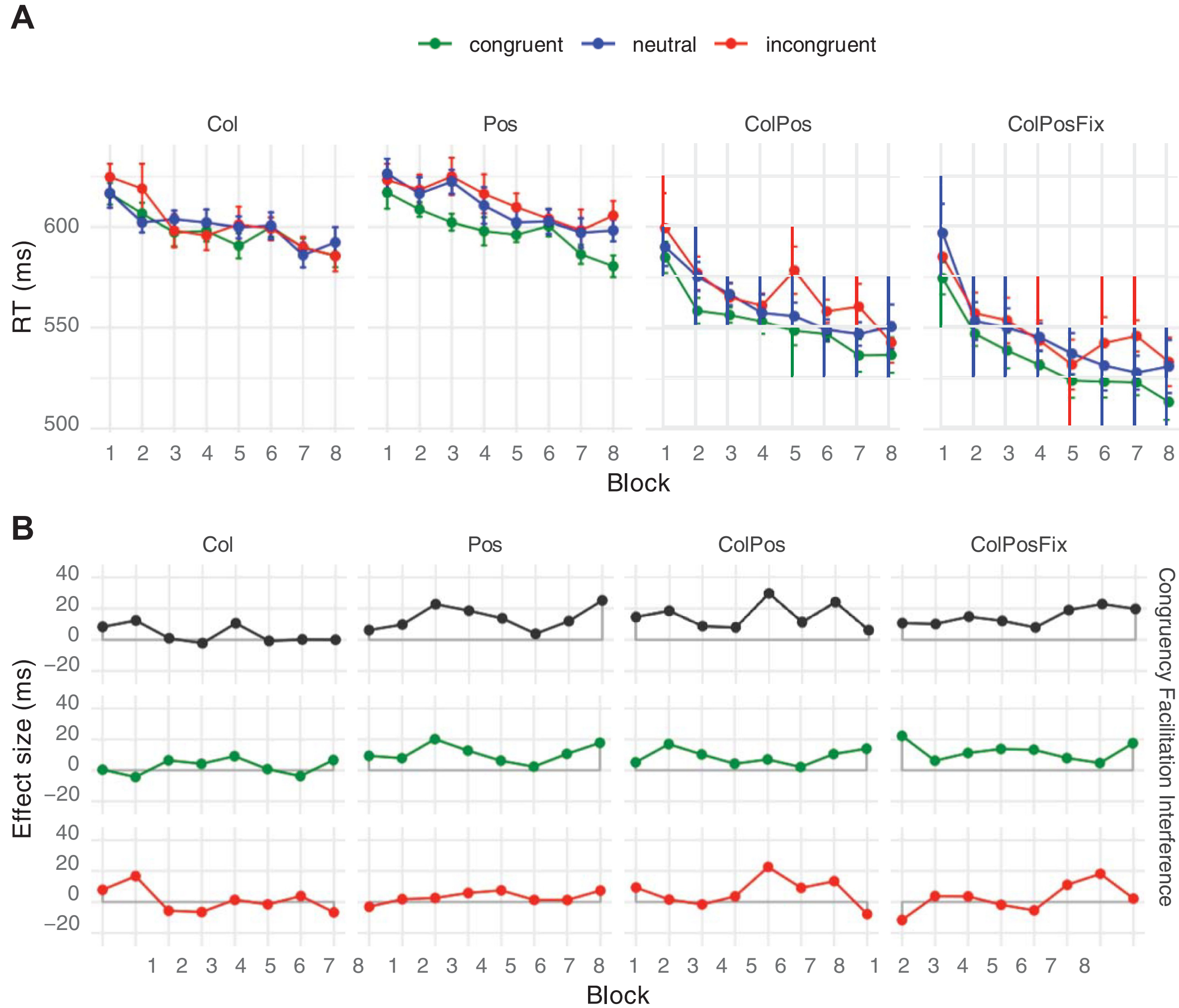

Fig 3. Mean response times (A) and net effects (B) in Experiment 1. Error bars are within-participant standard errors of the mean. Abbreviations: Col = color contingency, Pos = response position contingency, ColPos = both contingencies, ColPosFix = both contingencies plus fixed spatial arrangement of the response cues. Effects: Congruency = RTincongruent–_RTcongruent, Facilitation = RTneutral–_RTcongruent, Interference = RTincongruent–_RTneutral.

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Contingency awareness. Unfortunately, the files containing the descriptive statistics for the matching task were lost, but the originally calculated inferential statistics are available in the diploma thesis that also reported this experiment [34]. These offer the necessary information about whether participants could match pseudowords to colors and pseudowords to positions better than chance. With pseudowords from the ColPosFix contingency, participants could match pseudowords both to colors (t[9] = 2.86, p = .009, BF_{10} = 3.76) and to response positions (t[9] = 3.10, p = .007, BF_{10} = 5.11) with above chance performance, but the Bayes Factors indicate only moderate evidence for this. The Bayes-Factor of BF_{10} = 3.76 indicates that the observed pattern is almost four times as likely under the alternative hypothesis ('performance better than chance') than under the null hypothesis ('performance at chance level or worse'). For the Pos contingency, matching pseudowords to positions was not better than chance (t[9] = 0.43, p = .338, BF_{01} = 2.99). In the other conditions, Bayes Factors indicated that the data are inconclusive (BF_{10} close to 1; see Table A in S1 File, for details).

Discussion

Experiment 1 employed a novel paradigm to assess the emergence of semantic- and response-congruency effects during color-word-contingency learning. Overall, participants performed with sufficient ease and speed in this rather complex task. Responses were faster when both color and position were correlated with the stimulus pseudowords (*ColPos*-blocks), compared to conditions under which only one dimension was validly coupled with the pseudowords (Col- and Pos-blocks). As expected, responses were even faster when response positions remained constant across the entire block (ColPosFix-blocks). This pattern suggests that random variation in the presentation–either in the uncorrelated dimensions (Col- and Pos-blocks) or in the positioning of the non-relevant response cues (ColPos-blocks)–slows responding, as compared to blocks in which both dimensions are correlated and the color-to-response mapping is constant (ColPosFix-blocks).

Crucially, there was a statistically reliable congruency effect (congruent–incongruent) in response times, suggesting that participants were able to adapt behavior to the implemented stimulus-response contingencies. Overall, facilitation and interference effects were both reliable, relative to the neutral baseline, which corroborates results obtained by Lin and MacLeod [21]. Blocks with position contingencies (Pos, ColPos, and ColPosFix) yielded clear congruency effects, but the effects were numerically small and missed significance in color contingency blocks (see Fig 3). This is in line with previous color-word contingency learning studies [19], but, considering the relatively small congruency effects, the current design might not be sufficiently powerful to corroborate the apparent interaction of congruency and contingency type. Interestingly, congruency effects emerged very early but did not substantially change in size over the course of no less than eight blocks, which is again consistent with previous findings [21, 22]. It thus seems that the underlying learning processes are fast but, at least in our complex experimental setup with many stimuli, adaptation to the particular contingencies is limited to relatively small gains of about 10 to 20 ms.

In one of their studies on color-word contingency learning, Schmidt and De Houwer [29] tested whether the size of the congruency effect depends on participants having explicit information about the general underlying contingency (e.g., "each word in the experiment is presented most often in a certain color"), paired with the instruction to learn the contingency. Using three color-word pairs, congruency effects were slightly larger when participants had been informed about the word-color contingency than when not. Schmidt and De Houwer [35] tested whether revealing the specific word-color pairs (e.g., "the word 'month' is presented most often in red") influenced the congruency effect and reported a small but just significant effect in favor of this hypothesis. The aim of Experiment 2 was to test whether awareness of the contingencies affects the response-time pattern in our more complex setup.

Experiment 2

To check the influence of explicit knowledge of the contingencies, we re-ran Experiment 1, this time providing information about the general type of contingency (Color, Position, Color & Position) implemented in each upcoming block (similar to [29]). As in Experiment 1, we assessed awareness of the specific contingencies by having participants match the stimulus pseudowords either to the four colors, or to the four response positions.

Method

Participants. Twelve students (5 male, age: $M = 26.17$, $SD = 4.95$) who had not participated in Experiment 1 took part. Inclusion criteria, informed consent, and compensation were the same as in Experiment 1.

Procedure. Experiment 2 was identical to Experiment 1 except that, before each block, participants were informed about the contingencies to be expected in the following trials. For example, before color contingency blocks, participants read the statement: "BLOCKTYPE 1: COLORS. In the following block, you will see five different words. Four of these will frequently appear in a particular COLOR. Thus, the word can guide you to find the correct response color" (translated from the German instruction). Equivalent information was presented for each contingency type. Thus, participants were given the opportunity to observe and profit from the particular contingencies. In the final matching task, the neutral (uncorrelated) pseudowords of the different contingency types were now included, and a "neutral" matching option was provided on the response sheets. The chance level was therefore at 20%.

Analysis. Response times and error rates were analyzed as above.

Results

Mean response times and net congruency effects are presented in Fig 4. The pattern was very similar to that of Experiment 1: There was an 11 ms difference between congruent and

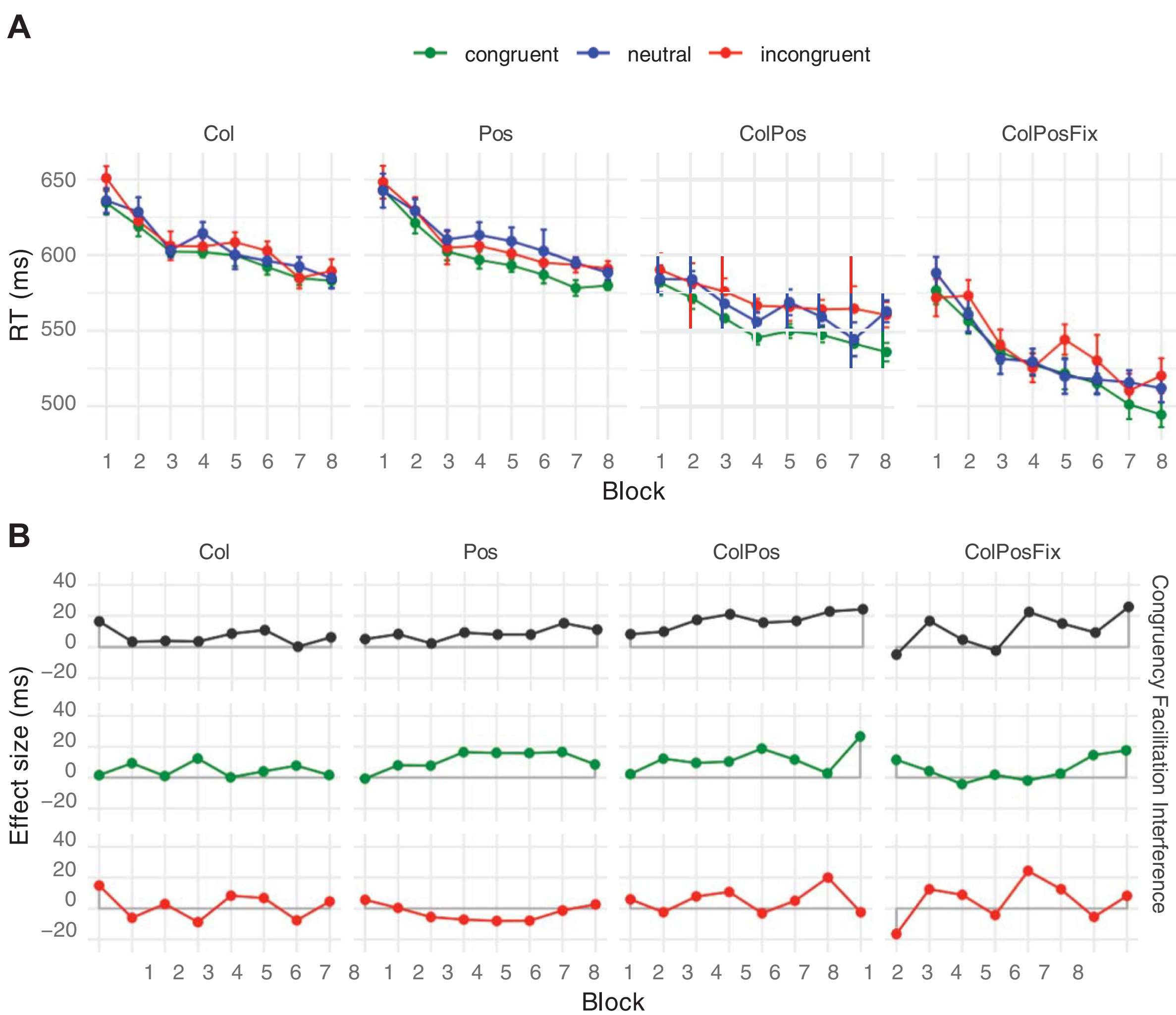

Fig 4. Mean response times (A) and net effects (B) in Experiment 2. Participants were informed about the contingency type before each upcoming block. Error bars and abbreviations as in Fig 3.

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incongruent trials (Exp. 1: 12 ms). The ANOVA on response times revealed a significant Congruency main effect, $F(2, 22) = 22.42$, $p < .001$, with overall faster responses on congruent (583 ms) than on neutral trials (591 ms), which in turn were faster than on incongruent trials (594 ms). The mean difference between congruent and neutral trials was small but reliable (8 ms, $t(11) = 6.08$, $p < .001$), but the difference between neutral and incongruent trials (3 ms) failed significance, $t(11) = 1.39$, $p = .193$. Mean response times again decreased with Block Repetitions, $F(7, 77) = 21.25$, $p < .001$, from 624 ms in Block 1 to 570 ms in Block 8. Finally, response times depended on Contingency Type, $F(3, 33) = 87.64$, $p < .001$, with the same pattern as in Experiment 1: Responses were slowest in Pos-blocks and in Col-blocks (both means 618 ms), faster in ColPos blocks (576 ms) and faster still in ColPosFix blocks (546 ms). Response time means in Col- and Pos-blocks did not reliably differ, $t(11) = 0.27$, $p = .800$, but mean Col-RT differed from ColPos-RT by 42 ms, $t(11) = 11.05$, $p < .001$, and mean ColPos-RT differed from ColPosFix RT by 30 ms, $t(11) = 5.31$, $p < .001$. Although none of the interactions was close to significance (all $F < 1.50$, $p > .192$), indicating congruency in all contingency conditions, we again tested our predictions for the different contingency types by separately assessing congruency effects. For all Contingency Types, responding on congruent trials was significantly faster than on incongruent trials (Col: 7 ms, $t(11) = 2.25$, $p = .046$, Pos: 8 ms, $t(11) = 2.66$, $p = .022$, ColPos: 17 ms, $t(11) = 4.42$, $p = .001$, ColPosFix: 11 ms, $t(11) = 3.07$, $p = .011$).

The error rate amounted to 3% of all trials and showed the pattern expected from congruency (congruent 2.6%, neutral 2.9%, incongruent 3.7%; see Figure A in S1 File); however, this Congruency effect failed significance, $F(2, 22) = 1.82$, $p = .186$, as did the other main and interaction effects (Contingency Type main effect: $F(2, 22) = 2.76$, $p = .057$, all other $F \leq 1.12$, $p \geq .361$).

Contingency awareness. In the matching task that followed the last block, participants performed better than chance when matching pseudowords from the ColPosFix block to colors, $M = 42\%$, $SD = 26\%$, $t(11) = 2.86$, $p = .008$, $BF_{10} = 8.23$. Despite congruency instructions, performance levels were close to chance under all remaining conditions (range of % correct matches: 18–28% (chance level = 20%) all $t[11] < 1.24$, $p > .121$) and either inconclusive or in favor of the null (BF_{01} between 1.08 and 3.48; see Table B in S1 File for details).

Joint analysis of Experiments 1 and 2. Because the different instructions in Experiments 1 and 2 did not seem to affect the pattern of latency effects, we ran a joint post-hoc analysis of the two experiments. The ANOVA of the combined data with Experiment as a between-participants factor revealed no reliable effects of this factor (main effect: $F(1, 20) = 2.43$, $p = .135$; all interactions with Experiment: $F < 1.33$, all $p > .273$). We therefore ran a joint ANOVA, collapsing the data from both experiments (Fig 5) to increase power. This joint analysis is based on data of 22 participants, each of whom contributed 2400 responses overall, resulting in 8448 responses for each contingency type.

Again, all three main effects turned out clearly significant, confirming the pattern from the individual experiments (all $F > 31.33$, all $p < .001$). Moreover, compared to the neutral condition, facilitation (9 ms) and interference (3 ms) effects were both reliable ($p < .05$). As before, most of the interactions turned out non-significant (Block Repetition × Contingency Type: $F[21, 441] = 1.34$, $p = .145$; Congruency × Block Repetition, $F[14, 294] = 0.92$, $p = .536$; Congruency × Block Repetition × Contingency Type: $F[42, 882] = 0.95$, $p = .562$). However, there was now a significant Congruency by Contingency Type interaction, $F(6, 126) = 2.61$, $p = .020$, suggesting that the size of the congruency effect was affected by the type of contingency. Indeed, although congruency effects were reliable for all contingency types, they clearly differed in size: Col: 5 ms ($t[21] = 2.62$, $p = .016$); Pos: 8 ms ($t[21] = 3.03$, $p = .006$), ColPos: 13 ms ($t[21] = 5.52$, $p < .001$) and ColPosFix: 11 ms ($t[21] = 5.29$, $p < .001$).

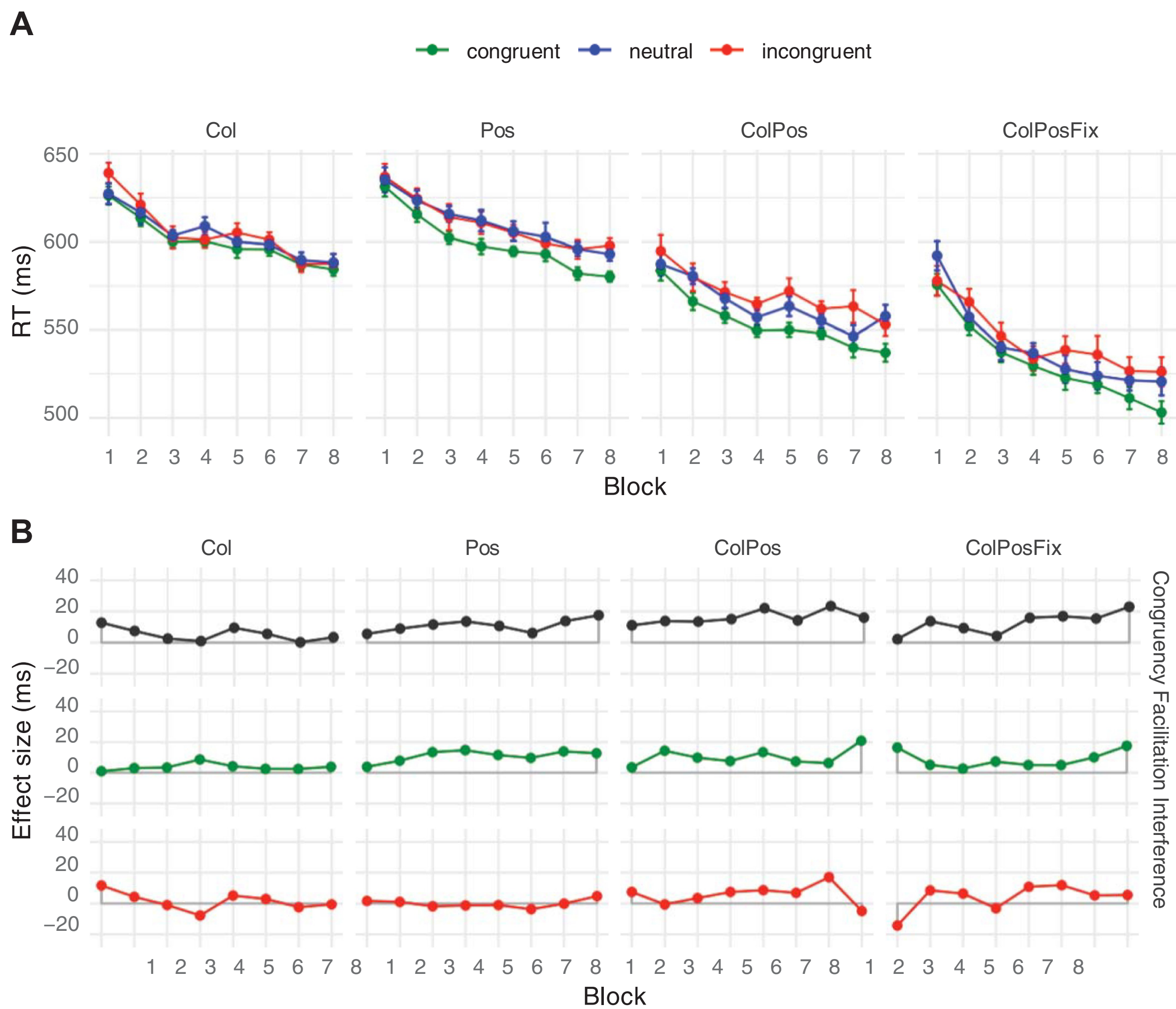

Fig 5. Mean response times (A) and net effects (B), collapsed over Experiments 1 and 2. Error bars and abbreviations as in Fig 3.

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Error rates from Experiments 1 and 2 combined followed the pattern expected from Congruency, with congruent, neutral, and incongruent trials leading to 2.61%, 3.00%, and 3.41% of errors, respectively. This was confirmed by a significant main effect of Congruency, $F(2, 42) = 4.11$, $p = .024$. None of the other main or interaction effects reached significance (all $F \leq 1.62$, all $p \geq .133$).

Discussion

Experiment 2 differed from Experiment 1 only in that participants were informed before each block about the contingencies in the upcoming trials. Despite this explicit instruction, participants were afterward unable to match pseudowords to colors and/or to positions, except for contingencies of the ColPosFix blocks, which also showed above-chance matching in Experiment 1. Note that this condition is most similar to the variant used in Schmidt and de Houwer, who observed contingency awareness as well as an impact of awareness of effect size [29]. In our case, however, latency effects, for example the overall congruency effect (12 and 11 ms), were virtually identical in Experiments 1 and 2, and their joint analysis provided no evidence that the different instructions had any influence on behavioral effects. Unlike what was observed by Schmidt and De Houwer, explicit instruction thus did not enhance contingency awareness and had no impact on congruency effects in our paradigm. In hindsight this is not surprising, as explicit instructions are probably far more effective when participants have to deal with few stimuli and contingencies (three stimuli, one contingency, in [29]), as compared to four contingency types, and 20 pseudowords that come in 32 different guises each.

In the joint analysis, both components of the congruency effect–facilitation and interference–were reliable, which replicates other findings (cf. [21]). The most important finding from Experiments 1 and 2 is the reliable congruency effect in the color-only contingency blocks, which suggests the existence of a semantic component in color-pseudoword contingency learning. This was corroborated by the joint analysis, with more statistical power than the individual experiments.

Experiment 3

In the preceding experiments, we used horizontally arranged color patches as response cues, such that each pseudoword's print color could be matched directly with the colored response cues on the screen. In Experiment 3, we replaced the colored response cues by color names printed in black. Obviously, this will slow responding, because matching the print color of the stimulus pseudoword with one the four black color words *rot*, *grün*, *gelb*, and *blau* necessitates at least one intermediate step: The retrieval of the German *name* of the pseudoword's color. This name can be matched to one of the four color words present on the screen, whose positions correspond to the response buttons (see Fig 6). The rationale for this variant was to give more leeway to semantic effects, as (color) words are closely tied to their semantics. The mapping from print color of the pseudowords to color patches involves visual features, whereas the mapping of print color to color names involves access to more abstract, linguistic information. Given the additional step, we expected prolonged response times, and predicted that the additional color-name retrieval facilitates semantic contingency learning.

Method

Participants. Nine students (6 male, age: $M = 22.44$, $SD = 2.70$) took part in Experiment 3. Inclusion criteria, informed consent, and compensation were the same as above.

Materials and procedure. Experiment 3 was a close replication of Experiment 1. The crucial change was that we replaced the color squares by their corresponding German color names (*rot*, *gelb*, *grün*, *blau*) in black print color. To minimize spatial position effects on reading times, these words as response cues were positioned in the corners of an invisible rectangle, centered on the fixation cross, thus equating their eccentricity (cf. Fig 6). To increase stimulus-response compatibility, the spatial arrangement of the response buttons approximated the rectangular display of the color words on the screen, allowing comfortable responding with the index and middle fingers of the hands. As in Experiment 1, participants were not informed about the underlying contingencies. Except for the changes detailed above, all details of procedure and data analysis, including the matching task for assessing contingency awareness, were identical to those in Experiments 1.

Results

Mean response times as well as net effects for Experiment 3 are shown in Fig 7. The pattern of response times again resembled those from Experiments 1 and 2. There was a clear and early-emerging congruency effect (of 28 ms) that was stable across contingency types and block repetitions. The ANOVA of the mean response times confirmed a significant main effect of Congruency, $F(2, 16) = 24.64$, $p < .001$. Responses were faster on congruent than on neutral trials

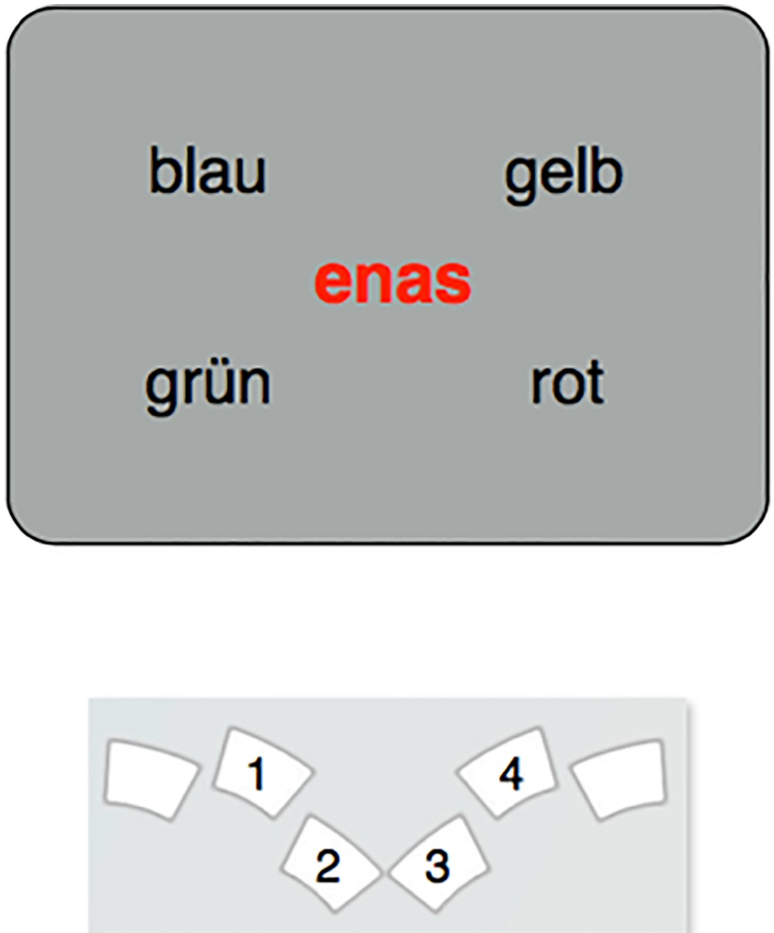

Fig 6. Stimulus display and spatial arrangement of response buttons in Experiment 3. Numbers on the response buttons are for illustrative purpose; they were not labelled in the experiment. In the sample trial shown here, response button 3 is the correct response.

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(784 ms vs. 811 ms, $t[8] = 5.69$, $p < .001$), and neutral trials did not differ from incongruent trials (812 ms, $t[8] = 0.46$, $p = .654$). Mean response times decreased significantly over Block Repetitions, $F(7, 56) = 47.86$, $p < .001$, from 956 ms in Block 1 to 729 ms in Block 8, and were affected by Contingency Type, $F(3, 24) = 102.69$, $p < .001$. Response speed did not reliably differ between Col- (940 ms) vs. Pos-blocks (938 ms), $t(8) = 0.38$, $p = .744$, but did so between Pos- and ColPos-blocks (696 ms), $t(8) = 8.96$, $p < .001$, as well as between the ColPos- and ColPosFix-blocks (633 ms), $t(8) = 6.16$, $p < .001$. None of the interactions turned out significant (all $F < 1.00$ and $p > .441$).

As in Experiments 1 and 2, we assessed the significance of individual congruency effects. The mean response time difference between congruent and incongruent trials was significant in all contingency conditions: Col: 29 ms ($t[8] = 3.43$, $p = .009$); Pos: 20 ms ($t[8] = 2.42$, $p = .042$), ColPos: 44 ms ($t[8] = 3.72$, $p = .006$) and ColPosFix: 19 ms ($t[8] = 2.76$, $p = .025$).

Error rates were slightly higher than in Experiments 1 and 2, now 3.97% (congruent 3.60%, neutral 4.20%, incongruent 4.12%; see Figure A in S1 File). The main effect of Congruency just failed significance, $F(2, 16) = 3.60$, $p = .051$. No other main effects or interactions reached significance, all $F < 2.27$, all $p > .106$.

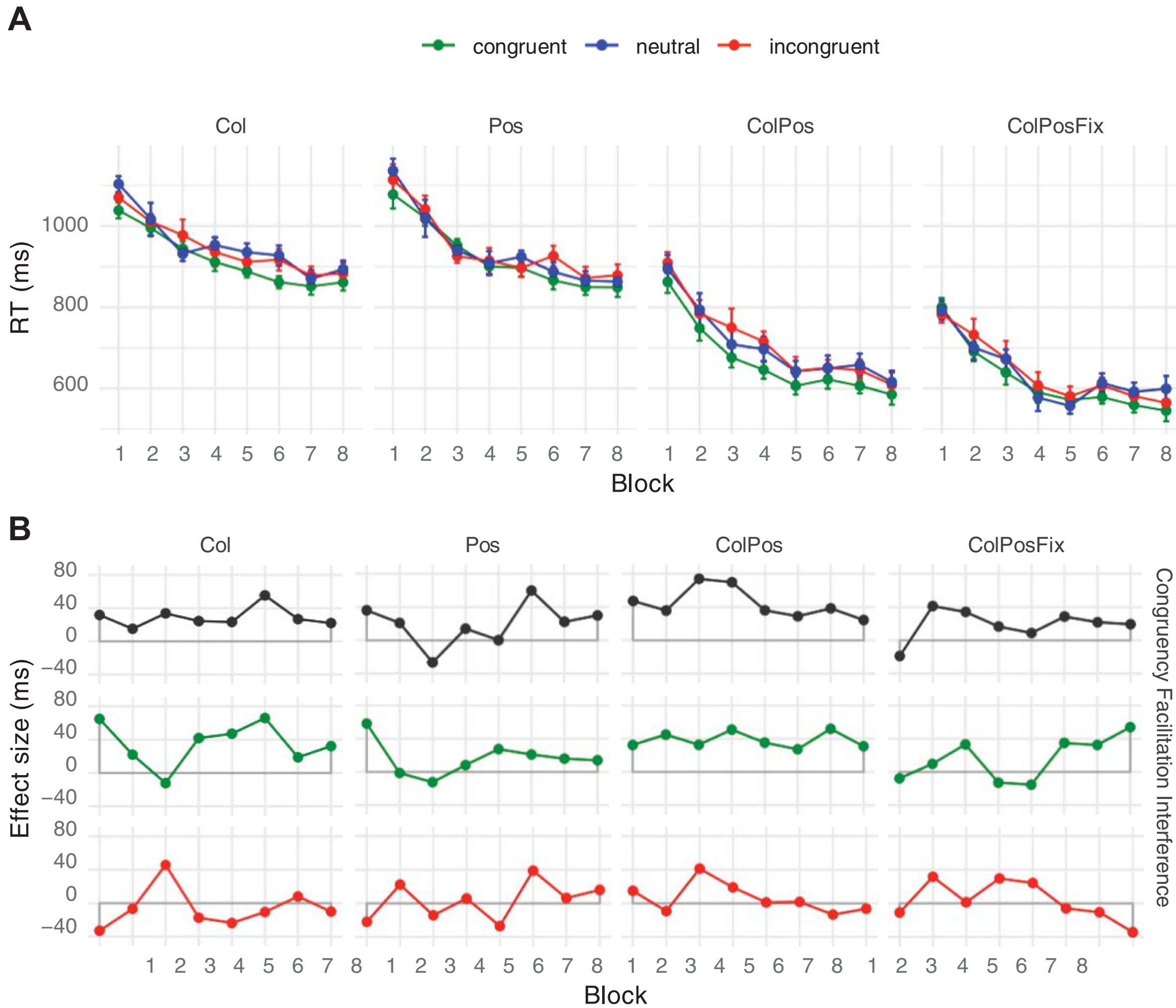

Fig 7. Mean response times (A) and net effects (B) in Experiment 3. Error bars and abbreviations as in Fig 3. Note the larger scale on the vertical axis, compared to the Figs 3, 4, and 5.

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Contingency awareness. The color-pseudoword matching performance after session 4 differed substantially across contingency types (range: 16–47%, chance level = 25%). As in Experiments 1 and 2, pseudowords from ColPosFix blocks were matched to their corresponding colors with better than chance accuracy (M = 47%, SD = 20%, $t(8) = 3.41$, p = .005, BF_{10} = 13.47). In the remaining conditions, however, neither color- nor position-matching performance was better than chance (all $t[8] < 1.49$, $p > .090$) and either inconclusive or in favor of the null (BF_{01} between 0.74 and 5.86; see Table C in S1 File for details).

Discussion

In Experiment 3, we tested whether replacing color patches by color words printed in black generates the same patterns of congruency effects, or allows for a clearer impact of semantic effects. As expected, the response-time range clearly changed, now spread over a much larger interval (from 550 to 1100 ms), as compared to Experiments 1 and 2 (from 480 to 630 ms). Color-only and position-only contingencies in particular had slower responses. When both color and position correlated with the pseudowords, however, correct responses were almost as fast as in Experiments 1 and 2.

Large increases in response time notwithstanding, the pattern of effects was similar to that in Experiments 1 and 2. Most importantly, there were robust congruency effects for all contingency types: from 19 and 44 ms in the two conditions with both color and position information to 20 ms for position-only and 29 ms for color-only information. The latter effect provides clear evidence for a semantic component in associative learning. Note that there was no interference in Experiment 3, which leads us to believe that interference arises when visual features–color in our case–are salient in the design. This clearly did not apply in Experiment 3, as the only color present on the display (or response buttons) was the print color of the pseudoword. Considering congruency effects within blocks, all but two out of the 32 (8 blocks x 4 congruency types) combinations showed faster mean response times on congruent trials than on incongruent trials. This congruency effect was present early on, and there was no indication that it increased significantly across the eight blocks. That contingency learning effects can arise so quickly, within a small number of trials, is evidence of the efficiency of associative learning. Experiment 4 provides additional, unintended support for its remarkable speed and plasticity.

Experiment 4

The logic and intention of Experiment 4 were the same as for Experiment 1. In fact, Experiment 4 was actually designed and run as the first experiment in the series. Only when we analyzed the data did we discover a subtle programming bug which, however, turned out to provide valuable insights into the dynamics and stability of the implicit-learning processes. The effect of the programming bug was that—different from what we had intended—the pseudoword-color and/or pseudoword-position contingencies did not remain constant throughout the experiment. Rather, although contingencies within any trial block were implemented as planned, they were re-randomized before each new block of trials. Since chances were slight that a pseudoword would remain associated with the same color or position from one block to the next, pseudoword-color and/or pseudoword-response contingencies that had been learned within one trial block could not facilitate responding in subsequent blocks. When one or more pseudowords are again presented but associated with a different color or position, this may result in negative transfer, as in learning experiments with an AB-ABr paradigm, in which the original stimuli and responses are re-paired [36, 37]. The data from Experiment 4 thus allow us to evaluate the speed of contingency learning within blocks, and to assess re-learning across blocks (cf. [21]).

Method

Participants. Thirteen students (4 male, age: $M = 23.69$, $SD = 3.07$) took part. Inclusion criteria, informed consent, and compensation were the same as above.

The experiment followed the same 4 x 3 x 8 experimental design, crossing Contingency Type (Col, Pos, ColPos, ColPosFix), with Congruency (congruent, incongruent, neutral) and Block Repetition (1 to 8). Within each block of 75 trials, a fixed subset of five pseudowords was used: one neutral control pseudoword and four experimental pseudowords of the same type (either Col, Pos, ColPos, or ColPosFix). Each pseudoword appeared as a colored stimulus on 15 trials per block.

Procedural details were identical to those of Experiment 1, except for the following. For each participant, pseudowords were randomly partitioned into four groups of five, one for each of the four contingency types—as in Experiments 1–3. However, this assignment applied to the current trial block only. Before the next trial block of that condition, all 20 pseudowords were again randomly reassigned to the four color and/or position conditions. Thus, the mapping of pseudowords to particular colors or response positions was re-shuffled from one block to the next. Unknown to the participants (and to the experimenters), any implicit associations from pseudowords to colors, response positions, or their conjunction that had been established within any one block became useless or even detrimental in the next trial block of that condition.

Remarkably, none of the participants reported having noticed any change of stimulus-response contingencies between trial blocks and sessions. In fact, we discovered the programming bug only when we (disappointed by the absence of any learning effects in the overall data) scrutinized the stimulus-generating programs. However, because stimulus-response contingencies were as planned within, but randomly re-assigned between blocks, we checked the data for traces of implicit learning within trial blocks. To do so, we subdivided each block into five non-overlapping segments ('sub-blocks') of 15 trials each and checked whether and how mean RTs and error rates (averaged over all eight repetitions of a given contingency type) changed within blocks. Moreover, the final segments of the blocks were analyzed in a repeated-measures ANOVA with the factors of Congruency and Contingency Type.

Results

In all contingency conditions, responding in the last segment of blocks was faster in the congruent than in the incongruent condition, by 10 ms on average (see Fig 8). Analysis of mean response times in this last segment revealed main effects of Congruency ($F(2, 24) = 5.46$, $p = .011$), and of Contingency Type ($F(3, 36) = 7.43$, $p < .001$), but no reliable interaction ($F(6, 72) = 0.92$, $p = .486$). For the mean overall 10 ms congruency effect, pairwise t-tests showed that responses on congruent trials (543 ms) were slightly but not significantly faster than those on neutral trials (547 ms), $t(12) = 1.61$, $p = .132$, whereas responses were faster on neutral than on incongruent trials (553 ms), $t(12) = 2.38$, $p = .035$ (see Fig 8).

Error rates in the final block segment were between 1.7% and 3.6% but showed the expected pattern only in the Pos and ColPosFix conditions. None of the main and interaction effects turned out reliable in the repeated-measures ANOVA on the arcsine square-root transformed error rates (Contingency Type: $F(3, 36) = 0.24$, $p = .868$; Congruency: $F(2, 24) = 1.47$, $p = .250$; Contingency Type × Congruency: $F(6, 72) = 0.98$, $p = .445$).

Discussion

Experiment 4 assessed whether there are traces of implicit learning even when the contingencies between stimulus pseudowords and their print color and/or correct response position within each contingency condition are randomly reshuffled from block to block. Our results show that this is indeed the case: Response times in the final block segments yielded an overall 10 ms congruency effect. Interestingly, the interference portion (6 ms) of this effect was significant, and numerically larger than its facilitation portion (4 ms). There was no evidence that the size of the congruency effect was modulated by contingency type, but a differentiation is difficult given the limited number of learning trials for any pseudoword-color or pseudoword-position pairing. Nevertheless, the data from Experiment 4 reveal that, in spite of the task complexity and the non-intended changes of the stimulus-response contingencies from block to block, color-word contingency learning can swiftly lead to congruency differences in response times, even within single blocks that contain 12 congruent and 3 incongruent trials only for any given pseudoword. Contrary to Experiments 1 and 2, the congruency effect mainly consists of interference for incongruent pairings. This is not surprising given the negative transfer

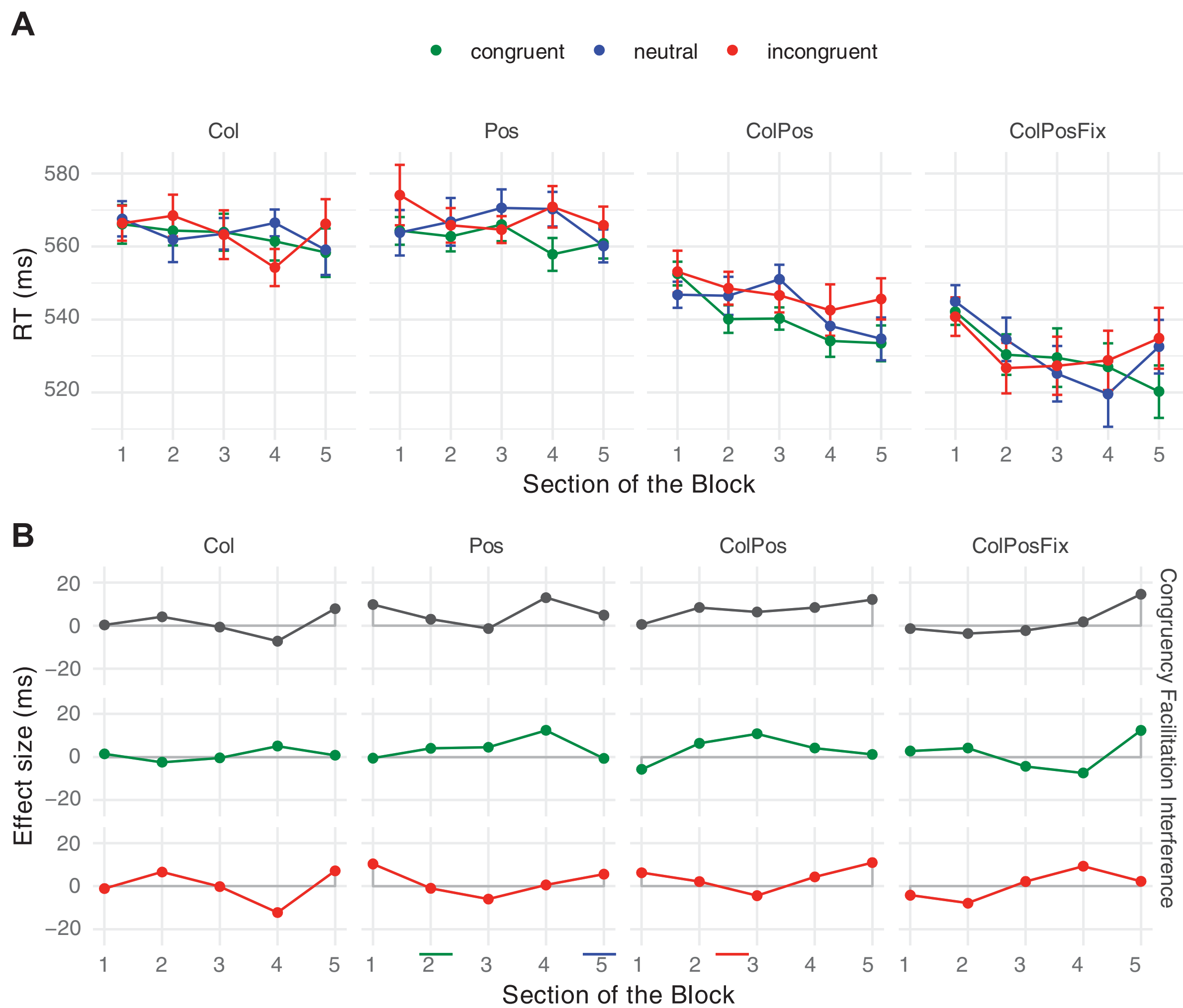

Fig 8. Mean response times (A) and net effects (B) in Experiment 4. Error bars and abbreviations as in Fig 3.

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of former color/position contingencies and relearning of new ones. Experiment 4 thus provides interesting insights into learning and re-learning of contingencies in our paradigm, and the data are in line with results by others who obviously acquired their data deliberately [21, 22, 38].

General discussion

In four experiments, we investigated the mechanisms underlying color-word contingency learning in the color-matching task. Our goal was to disentangle potential semantic and response-learning contributions to the learning effect. We employed a novel variant of the paradigm in which a row of color patches (Experiments 1, 2, and 4) or a set of color words printed in black (Experiment 3) on the screen indicated which of four response buttons corresponded to which of the four print colors on a given trial. This design allowed us to independently manipulate pseudoword-to-color and pseudoword-to-response-position contingencies. In fact, we implemented separate contingency conditions in which different pseudowords were associated either with print color (Col), with spatial position of the assigned response (Pos), or with both (ColPos). In the fourth contingency type (ColPosFix), the pseudowords were also associated with both color and response position, while keeping the spatial order of the response color patches/words constant throughout the experiment. This latter condition closely resembles the situation used in most previous experiments, with a fixed set of colored response buttons. Importantly, participants adapted to the particular contingency–and thus learned—with all four contingency types.

Overall, the response-time gains and losses caused by the different contingency types were small but statistically reliable. With color patches as response cues (Experiments 1 and 2), the strongest congruency effects were seen in conditions that contained position contingencies (effects between 8 and 13 ms), but the color-only contingency condition also revealed a small and reliable semantic (pseudoword-color) learning effect (5 ms). With color words printed in black as response cues (Experiment 3), effects were substantially larger (around 30 ms on average) and more similar across the different contingency types (see Table D in S1 File for summary statistics of all experiments).

Evidence for interference on incongruent trials (relative to neutral ones) was present in Experiment 1, and in the combined analysis of Experiments 1 and 2. The net interference RT effects across contingency types was 3 ms, which is smaller than the net facilitation effect of about 10 ms. Other studies find more sizeable interference, but also larger facilitation effects [21]. This difference in effect size is likely due to the use of many different stimuli in the present study and the fact that, within each trial block, incongruent trials involved each correct response position and/or color just once. Interestingly, interference was larger in Experiment 4, which we interpreted as a sign for learning and re-learning, as the pairing of pseudowords and colors/positions was reshuffled after each block. Also of interest, there was no hint of interference and but substantial facilitation in Experiment 3, when color words instead of color patches were used. We believe that interference in the standard stimulus color to color-patch (or color-button) version may be due to competing visual features (color, in this case) that are saliently present, as compared to color words written in black.

Our experimental design was much more complex than in previous color-word contingency learning studies. The different types of contingency were manipulated within-participants, in separate blocks, with a neutral control word in each contingency condition. Throughout the experiments (except for Experiment 4), participants were to process 20 pseudowords, and for 16 of these, contingencies existed that could be learned. To exclude mere context-specific visual learning effects (see [31]), we randomly varied font type and size of the pseudowords from trial to trial, such that each pseudoword appeared in any one of 32 physically different guises. Finally, when response cues alternated positions on a trial-by-trial basis, participants had to locate the correct response-button position first before executing the color-matching response. This certainly increased task demands, as compared to responding with color-labelled physical buttons. In spite of these design and stimulus characteristics, we obtained reliable and consistent congruency effects across contingency conditions and experiments.

The observation (in Experiments 1 and 2) that congruency effects were larger for response-contingency learning than for semantic learning replicates findings from the 2:1 mapping paradigm previously used to distinguish semantic and response learning. Schmidt and colleagues [19] reported a sizeable 26-millisecond congruency effect as evidence of response learning. Because there were no additional stimulus-match effects, they concluded that semantic learning contributes little to color-word contingency learning. This was different in our study, however: Participants did profit from semantic associations that existed in the color-only contingency blocks, where response-position learning was not possible. Our results clearly indicated that even such an incidental statistical association of words and colors is sufficient to foster semantic learning. Interestingly, a later study by Schmidt and colleagues [27] showed small but significant category-to-color learning, using many different instances of semantic (animals, professions) or linguistic (verbs) categories. This supports and extends our findings of specific pseudoword-to-semantics associations.

Our use of semantically neutral pseudowords rather than of meaningful words may well have facilitated semantic learning, as it is probably easier to learn semantic features for pseudowords such as "*enas*" that have no semantic representation, than for existing words such as "month" that do have a semantic representation but–for most of us–are non-specific for color. Finally, with color words rather than color patches as response cues (Experiment 3), semantic effects were as large as pure response-position effects, and as the effects of color and position combined.

Interestingly, our results provide no evidence for additivity of position and color contingencies. Purely semantic (Col conditions) and response-learning effects (Pos condition) do not add up to substantially larger effects in the combined conditions (ColPos and ColPosFix). This was most obvious in Experiment 3, where the pure semantic and response-learning effects were relatively large and about equal in size (ca. 30 ms); however, effects in the combined blocks did not increase, as would be expected from additive accounts.

Next, in all four experiments, contingency effects emerged early on and did not reliably increase with repetition. The inadvertent data from Experiment 4 corroborate this: Even when contingencies are randomly reset from block to block, 12 congruent trials for any pseudoword seem to suffice to yield contingency adaptation. These findings are fully consistent with those of Schmidt et al. [22], a single-session study, and experiment 2 of Lin and MacLeod [21].

An important insight from our experiments concerns contingency awareness. Experiments 1 and 2, with color patches as response cues, differed with respect to instructions only; in Experiment 2, but not in Experiment 1, participants were informed about the global type of contingency present in each upcoming block (color, position, or both). This explicit information did not affect response times, however, nor did it influence the contingency-awareness data collected afterwards. We were thus unable to induce contingency awareness to an extent that made a difference in the post-learning assessment of Experiments 1 and 2. This contrasts with results of Schmidt and De Houwer [29], who did observe significantly larger congruency effects when participants were informed about, and indeed aware of, the type of contingency, than when not. Note, first, that the only condition in which our participants were above chance level in their contingency awareness was the ColPosFix condition that is very similar to the standard version used in most studies, including Schmidt and De Houwer [29]. Next, their experiment included one type of contingency and only three word stimuli, which certainly may have facilitated focusing on this one type of association, as compared to our more complex design.

In sum, our findings suggest two important properties of the underlying learning process:

(1) This type of learning is powerful: In spite of the incidental and actually task-irrelevant associations with which pseudowords are presented, participants need just a few trials to optimize behavior to the additional information provided by the color and/or response contingencies.

(2) The influence of these learned contingencies on response time does not depend on contingency awareness, and seems limited: Congruency effects do not substantially increase with block repetitions. This is particularly surprising given the swift initial learning. It may be that the incongruent and neutral trials within each block, along with the conflicting information from other blocks (e.g., other words associated with the same colors/positions), discourage participants from relying more strongly on the learned associations.

How do our results relate to previous studies on semantic novel-word learning and to language learning in general? Most previous studies that investigated semantic learning from statistical association used richer semantic input and employed more explicit learning paradigms [5, 7, 8, 11] . In contrast, our participants merely had to match the pseudoword's ink color to the corresponding color patch or word, which required no attention to the pseudoword itself. Indeed, the contingency-awareness task showed that participants did not match pseudowords from the Col blocks any better than chance, suggesting that no explicit pseudoword-color links were available. Interestingly, the only evidence for above-chance matching was found in the ColPosFix condition that mimicked the classic color-word contingency learning experiment with confounded color and position learning [19]. Based on the participants' report of noticing the contingency or not, Schmidt and colleagues distinguished between subjectively aware and unaware participants, but they did not formally test any matching performance. Thus, despite not being able to report the contingencies, their participants might have been able to match words to colors with above chance accuracy.

Although the task in our experiments did not require any semantic processing and there was no explicit role for semantics (in contrast to previous, more explicit word-learning experiments), we observed a semantic effect (similar in nature to the effect from our Stroop study with pseudowords, see [8]). Thus, even associations presented in a purely incidental fashion, largely out of our attention's focus, seem to be monitored constantly to improve our repertoire of word-meanings links.

Given that sizeable semantic effects of even 30 ms were obtained in a highly complex design with four different contingency types, it seems worthwhile to replicate this finding in a simpler experimental context, focusing on the Col-blocks. It might also be worthwhile to test whether novel "color words" learned during color-word contingency learning are sufficiently associated with their color meanings as to produce more indirect semantic effects, such as behavioral semantic priming, or an N400 reduction in event-related potentials. Such effects would be directly comparable to more general semantic learning effects observed in our earlier studies [5, 7, 9].

In summary, our variant of color-word contingency learning with color cues on screen is a suitable tool for separating semantic and response-learning components. Our findings confirm previous studies that reported clear evidence for response learning in color-word-contingency learning. Over and above those findings, we here demonstrated unequivocal semantic learning effects, showing that incidental learning via statistical association can be sufficient to establish effective word-meaning links.

Supporting information

S1 File. Supplementary materials. Error rates and matching performance for Experiments 1, 2, and 3.
(PDF)

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Author Contributions

Conceptualization: Sebastian Geukes, Dirk Vorberg.

Data curation: Sebastian Geukes.

Formal analysis: Dirk Vorberg.

Investigation: Sebastian Geukes.

Methodology: Sebastian Geukes, Dirk Vorberg.

Software: Sebastian Geukes, Dirk Vorberg.

Supervision: Pienie Zwitserlood.

Visualization: Sebastian Geukes, Dirk Vorberg.

Writing – original draft: Sebastian Geukes, Dirk Vorberg, Pienie Zwitserlood.

Writing – review & editing: Dirk Vorberg, Pienie Zwitserlood.

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