

Visual experience forms a multidimensional pattern that is not reducible to a single measure: Evidence from metacontrast masking

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A metacontrast masking paradigm was employed to provide evidence for the richness and diversity of our visual experience. Square- and diamond-shaped targets were followed by square- and diamond-shaped masks at varying stimulus onset asynchronies (SOAs), resulting in shape-congruent and shape-incongruent trials. In Experiment 1, participants reported in each trial how they perceived target and mask. After extended training, seven different aspects of the target could be distinguished as specific percepts in this metacontrast masking paradigm. These percepts encompass aspects including the temporal distance between both stimuli, the perceived contrast of the target, and motion percepts resulting from the interplay between the target and mask. Participants spontaneously reported each of these percepts, and the frequency of reports varied systematically with SOA and the congruency between target and mask. In Experiment 2, we trained a new group of participants to distinguish each of these target percepts. Again, the frequency of reports of the specific percepts varied with SOA and congruency, just as in Experiment 1. In a last session, we measured objective discrimination performance yielding the typical individually different masking functions across SOAs. An examination of the relation between the frequencies of reports of subjective percepts and objective discrimination performance revealed multiple dissociations between these measures. Results suggest a multidimensional pattern of subjective experiences under metacontrast, which is reflected in dissociated subjective and objective measures of visual awareness. As a consequence, awareness cannot be assessed exhaustively by a single measure, thus challenging the use of simple one-dimensional subjective or objective measures in visual masking.

Introduction

Usually we have the subjective impression of a detailed representation of the entire visual scene, but phenomena such as change blindness and inattentional blindness suggest that even considerable changes in a scene may remain unnoticed (Irwin, 1991; O'Regan & Noë, 2001). These findings are often considered evidence that only objects within the focus of attention are represented in rich detail and that the world outside the focus of attention is only sparsely represented (Cohen, Dennett, & Kanwisher, 2016; Kouider, Gardelle, Sackur, & Dupoux, 2010). This discrepancy between the subjective impression of a rich perception and the objective evidence suggesting only sparse representations is taken as evidence of the fallibility of introspective methods that were developed in the beginning of the 20th century.

However, the common approach to evaluate participants' richness of perception might lead to underestimations because tasks focus on the identity of target stimuli, and participants' reports are restricted to categorical and object-centered dichotomies (Haun, Tononi, Koch, & Tsuchiya, 2017), such as, seen versus not seen, living versus non-living, or square versus diamond. This approach in experimental psychology typically neglects information about perceptual experiences related to simple sensations or stimulus features, such as, impressions of contrast or motion, that may contribute substantially to the richness of perception. To investigate the mechanisms that lead to phenomenological experience of visual stimuli and their neuronal basis it is therefore necessary to take such sensory or feature related experiences into account

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(Albrecht & Mattler, 2012a; Fei-Fei, Iyer, Koch, & Perona, 2007; Spillmann, 2009).

In recent years, methodologies to naturalize phenomenology have been proposed to systematically describe subjective experiences within a scientific framework (Dennett, 1991, 2003; Gallagher & Sørensen, 2006; Lutz, Lachaux, Martinerie, & Varela, 2002; Overgaard, 2004; Varela, 1996; Varela & Shear, 1999). Building on these earlier works, we suggest a three-step approach: First, we identified commonalities in idiosyncratic descriptions of subjective percepts across participants. Second, we parametrically manipulated experimental variables to trace back differences in subjective percepts to differences in experimental conditions. Third, we related subjective reports to objective performance in a discrimination task to validate the subjective reports as reliable perceptual cues that are utilized in the objective task. In the present study, we applied this approach in the context of metacontrast masking. To anticipate our results, we found evidence that even the perception of simple geometric figures under conditions of very weak stimulation can yield a complex and rich pattern of experiences.

Metacontrast masking occurs when a target stimulus is followed by a masking stimulus, whose contours fit neatly around the contours of the target stimulus (for a review, see Breitmeyer & Ögmen, 2006). One crucial determinant for the visibility of the target is the stimulus onset asynchrony (SOA) between the target and mask. Depending on the exact stimulation parameters, visibility either increases with increasing SOA (type A masking) or it follows a U-shaped masking function with the lowest visibility at intermediate SOAs (type B masking). Common methods to assess the awareness of a target stimulus in such paradigms encompass different kinds of objective and subjective measures. Objective measures refer to the correct detection, identification, or discrimination of a specific feature or the identity of a target stimulus (Breitmeyer & Ögmen, 2006). Subjective measures, in contrast, refer to the clearness of the perception of a stimulus (Del Cul, Baillet, & Dehaene, 2007; Overgaard, Rote, Mouridsen, & Ramsøy, 2006; Sandberg, Bibby, Timmermans, Cleeremans, & Overgaard, 2011; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010; Schwiedrzik, Singer, & Melloni, 2011; Sergent & Dehaene, 2004), to metacognitive judgments about one's own performance (e.g., confidence in an objective task; Szczepanowski & Pessoa, 2007; Szczepanowski, Traczyk, Wierchoń, & Cleeremans, 2013; Zehetleitner & Rausch, 2013), or to more indirect measures that assess the amount of money the participants are willing to bet on their decision in the objective task (post-decision wagering; Dienes & Seth, 2010a; Persaud, McLeod, & Cowey, 2007; Sandberg et al., 2010). All measures have in

common that they restrict the reports to predefined categories (correct vs. incorrect, seen vs. not seen), to a single dimension (e.g., magnitude of contrast), or to global measures such as the “clearness” of a stimulus. With such limitations, it is arguable whether any of these measures is suitable to measure consciousness exhaustively, or whether there can be a single measure at all.

Importantly, masking effects are shaped by the specific criterion content that is applied to the task. Criterion content refers to the perceptual cue, stimulus attribute, or psychological dimension on which a decision is based (Kahneman, 1968). It has been shown that criterion content changes with practice (Ventura, 1980) and differs between experimental conditions (Jannati & DiLollo, 2012) and participants (Albrecht, Klapötke, & Mattler, 2010; Albrecht & Mattler, 2012a, 2012b, 2016). Because different tasks require the use of different criterion contents, masking effects strongly depend on the specific measure that is used (Breitmeyer, Kafaligonul, Ögmen, Mardon, Todd, & Ziegler, 2006; Ansorge, Breitmeyer, & Becker, 2007; Ansorge, Becker, & Breitmeyer, 2009). With global measures (e.g., seen vs. not seen, clearness ratings), the criterion content is left undefined and is chosen by the participant, whereas other measures (e.g., contour discrimination) restrict the criterion content to specific and isolated aspects of the stimulus. Such a restricted focus is justified in some empirical contexts. For example, an investigation of priming effects of unconscious stimuli requires an assessment of conscious access of those stimulus features that potentially drive the priming effects (e.g., Mattler, 2003; Reingold & Merikle, 1988; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003).

However, in cases where the richness of subjective experience is in the focus of the research, any restrictions are suboptimal because it is widely acknowledged that the phenomenological experience of a target stimulus differs significantly across experimental conditions (Jannati & Di Lollo, 2012; Kahneman, 1968; Koivisto & Revonsuo, 2008; Sackur, 2013). Thus, although the objective performance may be the same with two different SOAs, the appearance and therefore the criterion content may differ substantially between both SOAs. In consequence, it is difficult to compare differences between subjective and objective measures across conditions (Jannati & Di Lollo, 2012).

Sackur (2013) employed multidimensional scaling (MDS) to map the perceptual space of metacontrast. Although SOA was the only independent variable (i.e., stimuli differed only along one physical dimension), Sackur found that perceptual space unfolded in three dimensions. The first dimension correlated highly with SOA (i.e., the levels of the independent variable were sorted in ascending order on the first dimension). The other two dimensions correlated with target

visibility at the descending and ascending branch of a U-shaped masking function, respectively (i.e., data were sorted according to the d' -values obtained in a discrimination task). Because the two latter dimensions reflected target visibility for different parts of the masking function, Sackur inferred that the target is perceptually different with short SOAs compared to long SOAs. Taken together, these results suggest that the subjective appearance of a target differs qualitatively across experimental conditions in a metacontrast masking paradigm. Consequently, we wondered whether one-dimensional subjective measures suffice to assess subjective awareness in metacontrast masking exhaustively.

Phenomenology in metacontrast masking

To the best of our knowledge, the phenomenological space of target percepts in metacontrast masking has not yet been systematically investigated, although [Werner \(1935\)](#) already reported that the appearance of the target might vary from trial to trial despite identical stimulation parameters. Most of the existing theoretical approaches and models of metacontrast do not explicitly focus on the different contents of the visual appearance. For example, models based on lateral inhibition ([Bridgeman, 1971, 2001](#)) or efficient masking ([Francis, 2003](#)) rely on a single measure of global target visibility. Other models consider only a few contents of visual appearance, such as the perceived contrast and contours of the target ([Breitmeyer & Ögmen, 2006](#)), the temporal integration and segregation of target and mask ([Reeves, 1982](#)) or apparent motion ([Burr, 1984; Kahnemann, 1967](#)). In contrast to these models, the perceptual retouch theory ([Bachmann, 1984, 1994; Kirt & Bachmann, 2013](#)) is compatible with a broad range of perceptual contents in metacontrast masking because it is explicitly unspecific with regard to the content of perception. It proposes that perceptual contents are determined by processes within specific cortical neural networks and that awareness of a content of perception is determined by delayed activity in the unspecific subcortical network. Thus, any information that is present in the specific network at the time when the unspecific subcortical activity “raises” the perceptual content into consciousness could, in principle, be part of the accompanying visual experience. Nevertheless, the existing research on metacontrast yields a number of notions about the appearance of the target related to three aspects: (1) the perceived contrast of the target, (2) the perceived temporal order of target and mask, and (3) apparent motion. In the following, we address each of these aspects seriatim.

First, the perceived contrast of the target is modulated by the mask (e.g., [Breitmeyer et al.,](#)

[2006; Kahneman, 1967; Neumann & Scharlau, 2007; Werner, 1935](#)). [Breitmeyer et al. \(2006\)](#) asked participants to adjust the contrast of a test patch to the perceived contrast of a target disc that was masked by metacontrast with varying SOAs. The results showed a U-shaped function with high perceived contrast with short and long SOAs and a low perceived contrast with intermediate SOAs. Similar results have been found when participants rated the perceived contrast of the target directly on a Likert scale ([Neumann & Scharlau, 2007](#)). At intermediate SOAs of 50 to 100 ms, this metacontrast suppression can reduce the perceived contrast to the background level so that the target is not experienced at all. This has been shown with simple light flashes as target and mask ([Alpern, 1953; Fehrer & Raab, 1962; Kahneman, 1967; Schiller & Smith, 1966; Weisstein & Growney, 1969](#)) and with contour-defined stimuli of either polarity ([Breitmeyer, Tapia, Kafaligonul, & Ögmen, 2008; Stewart, Purcell, & Pinkham, 2011](#)).

In addition, several studies have reported not only a reduction but also a reversal of perceived contrast under certain conditions ([Heckenmueller & Dember, 1965; Purcell & Dember, 1968; Stewart et al., 2011; Werner, 1935](#)). [Werner \(1935\)](#) used a black target disc and a black annulus as a metacontrast mask and reported that on 7% of all cases the inner field of the annulus appeared to be whiter than the gray background. More recently, [Stewart et al. \(2011\)](#) presented a small black target disk to the left or to the right of the fixation cross followed by two ring-shaped metacontrast masks on either side of the fixation cross. Participants indicated the side on which the target disc had been presented. Results showed that with a SOA of 20 ms participants systematically chose the wrong side, suggesting that they perceived the target side as brighter than the non-target side. Against this background, we expect at least three contrast-related percepts with specific time courses across SOAs: (1) the percept of Dark Target should follow a U-shaped function across SOAs, (2) the percept of No Target should follow an inverted U-shaped function, and (3) the percept of Bright Target should be reported only with short SOAs.

Second, the perceived temporal order of target and mask has been shown to change with increasing SOA. With short SOAs, participants frequently report perceiving the target and mask as a temporally integrated percept of a target within the inner contours of the metacontrast mask; with long SOAs, in contrast, participants frequently report perceiving the target and mask as two successive perceptual events ([Reeves, 1982](#)). Based on these findings, [Reeves \(1982\)](#) formulated his temporal integration and segregation model of metacontrast masking. According to this model, masking is strong when both temporal integration and temporal segregation of target and mask fail. This

is the case at intermediate SOAs, because successful temporal integration of target and mask enhances target visibility with short SOAs (Eriksen & Rohrbaugh, 1970; Scheerer, 1973; Scheerer & Bongartz, 1973), and successful segregation of target and mask enhances target visibility with long SOAs (Francis & Cho, 2008; Jannati & Di Lollo, 2012; Neumann & Scharlau, 2007; Reeves, 1982). Therefore, we expect two time-related percepts: (1) the percept target inside mask resulting from integration should be reported more frequently with short rather than long SOAs, and (2) the percept target before mask resulting from segregation should be reported less frequently with short rather than long SOAs.

Third, apparent motion emerges when two successive stimuli are presented under optimal spatiotemporal parameters (e.g., Korte, 1915; Wertheimer, 1912) and has been frequently reported in metacontrast paradigms. Importantly, several studies found motion percepts in backward masking without awareness of the target stimulus (Fehrer & Raab, 1962; Hogben & Di Lollo, 1984; Kahneman, 1967; Toch, 1956; Weisstein & Growney, 1969). Thus, the experience of apparent motion does not depend on the experience of two successive stimuli. This is in line with the spatiotemporal receptive field approach of metacontrast (Burr, 1984), according to which the sequence of target and mask activates neurons that have spatiotemporal receptive fields that are not only tuned to a specific position in space but also tuned to a specific temporal distance between two events. These neurons signal the existence of one moving object instead of two static objects, resulting in the experience of a motion without experience of the target.

In more recent studies on metacontrast masking that varied the shape congruency between target and mask (for example stimuli, see Figure 1), participants frequently reported a rotational motion when the target and mask differed in shape (Albrecht & Mattler, 2012a; Albrecht & Mattler, 2012b; Ansorge et al., 2007, 2009; Maksimov, Murd, & Bachmann, 2011). Albrecht and Mattler (2012a) assessed the subjective experiences of motion percepts. Within the same paradigm, participants reported two different motion percepts—an apparent rotation and an enlargement or extension of the target similar to an outward motion. Albrecht and Mattler (2012a) assumed that either motion percept results from an interaction between the target and mask; however, there was no clear relation between the SOAs and the frequency of motion percepts in their study. Due to the relatively few reports of motion percepts, the authors did not differentiate between the two motion percepts in their analysis. Nonetheless, they speculated that rotational motion and enlargement might be associated with long and short SOAs, respectively. In consequence, it seems necessary

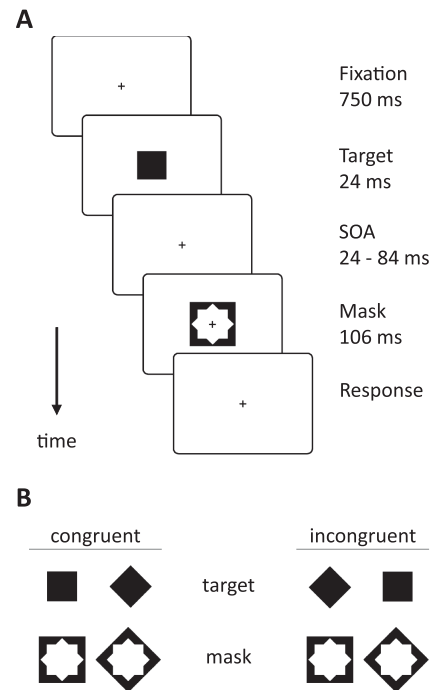


Figure 1. Trial sequence (A) and stimuli (B) that were used in all experiments.

to distinguish the two types of motion percepts to unveil their contrary relations with SOA.

Albrecht and Mattler (2012a) showed that participants who performed well with long SOAs in an objective target-discrimination task more often reported the subjective experience of motion percepts than participants who performed poorly with long SOAs. Beyond this, these well-performing participants also reported more often that they used motion percepts to discriminate the target shape in the objective task. Based on this previous study, we expected two different motion related percepts. The percept Rotation should be reported exclusively on incongruent trials and more frequently with long SOAs. In contrast, the percept Expansion should be reported independently of the target–mask congruency. Based on the counterintuitive findings of apparent motion without target awareness and the speculations in Albrecht and Mattler (2012a), we reasoned that expansion might be reported more frequently with shorter SOAs than rotation.

To sum up, the literature on metacontrast reported seven different target percepts that were associated with temporal and spatial relations between the target and the mask—namely, SOA and congruency. In addition, there is some evidence that individual differences in subjective reports relate to individual differences in objective performance. Most studies, however, suffer from two severe limitations by restricting themselves to very few different percepts and by determining the criterion content participants had to utilize. A

systematical investigation of the range of percepts that participants spontaneously report without restrictions is missing. Such a study could help to elucidate the richness of phenomenology in a metacontrast paradigm.

In line with the suggestion of [Haun and colleagues \(2017\)](#), we hypothesized that a fine-grained analysis of subjective visual experiences might reveal a rich visual phenomenology even for simple geometric figures under conditions of limited awareness due to visual masking. Our approach to assess the visual phenomenology is based on spontaneous reports of visual experiences across a variety of experimental conditions and allows a direct mapping of the perceptual space of visual experience even in conditions with starkly reduced stimulation. Hence, it has the potential to provide new evidence for the richness of conscious perception, which might pose strong implications for the different scales commonly used to assess conscious awareness.

Experiments 1a and 1b

We ran two phenomenological experiments to investigate (1) whether naïve participants are able to describe their visual experience of a metacontrast sequence, (2) whether these descriptions are related to percepts described in the literature, and (3) whether we can identify specific relations between distinct percepts and experimental conditions. These findings would validate our phenomenological approach and would provide direct evidence for the view that the spatiotemporal relation between the target and mask determines the quality of the visual experience on several distinct dimensions.

Materials and methods

Participants

Overall, 39 naïve students participated in [Experiment 1a](#) and [Experiment 1b](#) ([Experiment 1a](#): $n = 15$, 9 females and 6 males, ages between 20 and 29 years, mean \pm $SD = 22.5 \pm 3.1$ years; [Experiment 1b](#): $n = 24$, 17 females and 7 males, ages between 19 and 33 years, mean \pm $SD = 22.7 \pm 3.4$ years). Both experiments were comprised of five sessions that lasted between 60 and 90 minutes each. Four participants ($n = 2$ in each experiment) were excluded after the third session because they did not comply with the instructions. Two further participants ([Experiment 1b](#)) were excluded due to computer malfunction in at least one of the Sessions 4 or 5. Therefore, all analyses and figures are based on the data

of the remaining 33 participants. All participants were from Georg-August University Göttingen, had normal or corrected-to-normal vision, and received a monetary reward for participation. All participants were naïve with regard to the aim of the study and never had participated in a metacontrast masking experiment before. All experiments of this study were approved by the local ethics committee of the Georg-Elias-Müller-Institute of Psychology, Georg-August-University of Göttingen, and all experimental procedures are in accordance with the Declaration of Helsinki.

Tasks

In all sessions, participants verbally gave subjective reports about their visual experiences of metacontrast masked targets on each trial. In short, they accomplished three different tasks across different phases of the experiment: (1) they freely described their visual experiences in detail, (2) they summarized these descriptions into idiosyncratic categories of their most common experiences, and (3) they used these categories in the last phase of the experiment to classify their experiences on each trial. Participants were informed about the shape of targets and masks but not about the varying SOAs. In the training phase (Sessions 1–3), participants were trained to verbally report their subjective visual experience of the presented stimuli as detailed as possible on each trial. It was strongly emphasized that the task was to report the entire visual experience of the stimuli and not simply to identify the shape of the target. In [Experiment 1a](#), the instruction stated (translated from German): “*On each trial, please describe your visual experience of target and mask, even if the target can hardly be seen. Do not just report the shape of the target stimulus.*” In [Experiment 1b](#), only the target was mentioned in the instruction to prevent participants from describing only aspects of the clearly visible mask. The instruction stated: “*On each trial, please describe your visual experience of the target, even if it can hardly be seen. Do not just report the shape of the target stimulus.*”

Participants who were not reporting more than the shape of the target were excluded after the training phase because we interpreted this as a failure to comply with instructions ($n = 2$ in each experiment; see above). At the end of the training phase, each participant summarized his/her experiences into a list of idiosyncratic categories and gave each category a concise label (e.g., mask, spot, star, continuum [translated from German]). There were no constraints on the number of categories. In the test phase (Sessions 4 and 5), participants used these idiosyncratic categories to classify their subjective experience on each trial.

Stimuli

The target stimuli were filled squares and diamonds with a diameter of 1.5° of visual angle. The mask had a square- or diamond-shaped outer contour with a diameter of 2.6° of visual angle and a star-shaped inner contour that neatly surrounded the contours of the target, leaving space for 1 pixel (0.02° of visual angle). All stimuli were presented in black (0.03 cd/m^2) on a light gray background (72.3 cd/m^2) in the center of the screen of a CRT monitor (ViewSonic GF90-B, Brea, CA), with a refresh rate of 85 Hz. Target and mask durations were 24 ms and 106 ms, respectively. The SOAs between the target and mask included 24, 36, 48, 60, 72, and 84 ms. On half of the trials, the target and mask were congruent; that is, both stimuli were either squares or diamonds. On the remaining half of the trials, target and mask were incongruent; that is, one stimulus was a diamond and the other one was a square or vice versa (Figure 1B).

Procedure

The experiments took place in a dimly lit room with participants' heads resting on a combined head- and chin-rest 100 cm from the screen. The trial sequence was identical for all five sessions (Figure 1A). Each trial began with a fixation cross for 750 ms followed by the target for 24 ms and the mask for 106 ms. After presentation of the stimuli, participants had unlimited time to give a verbal response. In Sessions 1 to 3, they freely described their visual experience. In Sessions 4 and 5 they named one of the categories from their individual list, which they had created at the end of Session 3. Utterances were recorded on a hard disk using a boundary-layer microphone placed in front of the monitor. Participants ended each trial by a key press. After a random inter-trial interval between 750 ms and 1250 ms, the next trial began. Participants were instructed to fixate the cross over the entire trial.

Unless stated otherwise, the independent variables of target (square vs. diamond), mask (square vs. diamond), and SOA (24, 36, 48, 60, 72, or 84 ms) varied pseudorandomly within each block so that each of the 24 combinations occurred equally often.

In the training phase, Session 1 was comprised of six warm-up blocks with four trials each and three (Experiment 1a) or two (Experiment 1b) training blocks with 24 trials each. Across the warm-up blocks, SOA varied blockwise in random order. Each target-mask combination occurred once per warm-up block in random order. Participants were instructed to carefully observe the stimulus sequence and reflect on their visual experience of the stimuli; they did not give any verbal reports. In the training blocks, participants gave detailed verbal reports about their visual experience on each trial. They could repeat each trial as often as

they wanted (Experiment 1a) or twice (Experiment 1b) by pressing the space bar. After every 5 to 10 minutes, participants were asked to take a short break, during which the experimenter repeated the instructions in a standardized way. If the three training blocks were not finished within 1 hour, the session was terminated. At the end of the session, participants described their most common visual experiences in detail and additionally drew a sketch for visualization.

Sessions 2 and 3 were identical to Session 1, except that the warm-up blocks were omitted, and each trial could be repeated only twice and only in the first training block. At the end of Session 3, participants summarized their most common visual experiences of the first three sessions and created a list of idiosyncratic categories sufficient to describe the entire range of visual experiences of the individual participant. Two additional training blocks followed, in which participants classified their visual experiences on each trial into one of their idiosyncratic categories. Only one category of the list could be named on each trial. After each of the two blocks, participants were allowed to modify their list of categories. The average number of trials performed during the training phase across the first three sessions was 245.69 ($SD = 39.62$) for Experiment 1a. In Experiment 1b, each participant performed a fixed number of 264 trials during the training phase.

The test phase included Sessions 4 and 5. Both sessions consisted of one warm-up block with 24 trials and seven experimental blocks with 48 trials each. The warm-up block was excluded from all analyses. On each trial, participants classified their visual experience by uttering the name of one of their idiosyncratic categories and began the next trial by key press. During the warm-up block, the experimenter stayed in the room, and the participants could repeat each trial twice. In the experimental blocks, participants could not repeat trials. At the end of both sessions, participants received a careful debriefing identical to that in the training phase. Altogether, the test phase was comprised of 672 experimental trials, 56 trials per condition ($6 \text{ SOA} \times 2 \text{ congruency}$).

Data analysis

Two raters classified the idiosyncratic verbal descriptions of the percepts that participants had crafted at the end of the training phase into one or more of the seven percept categories that we had extracted from the literature: (1) Target inside Mask, (2) Target before Mask, (3) Dark Target, (4) Bright Target, (5) No Target, (6) Rotation, or (7) Expansion. Descriptions that did not fit in any of these categories were classified as Other. Raters were informed about the set of descriptions that were given by the same participant. They were told in detail about the literature-based

categories, but they were naïve regarding the two different experiments and the design and the aim of the study. The order of the participants was randomized for each rater. Inter-rater reliability was assessed by Cohen's κ (Cohen, 1960) separately for each category and experiment.

Data from the test phase were pooled across the two sessions. First, we calculated the absolute frequency of each idiosyncratic description separately for each participant, SOA, and congruency. Second, in order to report summary statistics across participants, we recoded the idiosyncratic descriptions into the percept categories according to the judgment of both raters, and we calculated the absolute frequency of each of these percept categories separately for each participant, SOA, and congruency. If several descriptions of one participant were rated into the same category, the absolute frequencies of these descriptions were summarized for this participant.

We examined the influence of SOA and congruency on the report probability for each percept category separately using a factorial design. All analyses were done by means of resampling tests: We computed t -test statistics for the main effect of congruency, for linear and quadratic trends of SOA, and for the interaction of these trends with congruency. We then compared the observed test statistics with a permutation distribution of test statistics given the null hypothesis. The proportions of the permutation distribution that yielded an equal or higher t -value than the observed t -value reflect the probability of a false-positive result (i.e., p value). The permutation distribution was comprised of 10,000 independent simulations using single-trial data of each participant. For each simulation, we randomly assigned the actually given reports of each participant to the different conditions and treated the simulated dataset identical to the observed dataset. Thus, we kept the absolute number of trials for each participant and the absolute number of each idiosyncratic description constant; only the assignment to the different SOA and congruency conditions differed. We conducted all tests for both raters separately and report the effects as significant when $p < 0.05$ for both raters. Unless otherwise noted, we always report the higher of both p values.

Results

Training phase (Sessions 1–3)

Out of the 39 participants who took part in the first three sessions, 35 reported rich and detailed visual experiences in the training phase. Two of these 35 participants were excluded from all analyses due to computer malfunction in the test phase, so that all of the following results are based on

$n = 33$ participants. The total number of spontaneous descriptions given at the end of the training phase was $N = 90$ and $N = 158$ for Experiment 1a and Experiment 1b, respectively. Table 1 shows some generic examples and their classification to the respective categories. On average, each participant collected a mean of 6.9 ($SD = 3.8$) and a mean of 7.9 ($SD = 3.1$) idiosyncratic descriptions in Experiment 1a and Experiment 1b, respectively. Inter-rater reliability was moderate to high for most categories in both experiments (Table 2); only the categories target inside mask and target before mask showed only poor to fair agreement among raters for both experiments. Nevertheless, the data patterns are highly similar regardless of the ratings on which the analyses are based. To facilitate communication, we report results based only on one rater unless mentioned otherwise. The results based on the second rater are provided as Supplementary Information.

In Experiment 1a, 50% of all descriptions matched at least one of the seven percept categories (i.e., 50% were classified as Other). In Experiment 1b, 80% of all descriptions matched the seven percept categories (i.e., 20% Other). Each category included descriptions of several participants (Figure 2A), and each participant described at least one of the seven percept-categories found in the literature (Figure 2B). The median number of categories that were necessary to cover the descriptions of a participant was higher in Experiment 1b than in Experiment 1a (median = 4 vs. median = 3; $W = 136.5$; $p = 0.001$). These findings show that the visual experiences of participants are reflected to a substantial degree by the seven categories.

Test phase (Sessions 4 and 5)

In the test phase, most participants used all of their idiosyncratic categories that they had generated in the training phase. Only two participants used fewer categories in the test phase than they had generated in the training phase (10 instead of 13, and 14 instead of 16 descriptions, respectively), so that the total number of categories in Experiment 1b in the test phase was $N = 153$. Because the pattern of data from the training phase was very similar across both experiments, we pooled the data for the analysis of the test phase. Figure 3 shows the mean frequency of reports for each perceptual category as a function of congruency and SOA. In addition, we show the number of participants who reported the respective percept at least once. It can be clearly seen that there are marked differences in the number of reports for each percept. Moreover, the number of reports of specific percepts varies in different ways with SOA. In the following, we itemize each perceptual category one after the other (for a list of all effects, see Table 3).

1. Target inside Mask	<ul style="list-style-type: none"> - The inner form of the mask clearly filled the target. The target disappears, but before it was well visible. - Small target is located inside the star of the mask. - Target as a black square seems to luminesce clearly inside the white part of the mask, as if the white square seems to pulsate.
2. Target before Mask	<ul style="list-style-type: none"> - Target was separated from the mask and was difficult to recognize. - A black, filled Target always with the same form and size as the mask appears. Target and mask appear successively. - Target is easy to perceive. The trial seems to be slower, so that target and mask can be perceived successively. First a black target with all edges and borders is visible and afterwards a mask.
3. Dark Target	<ul style="list-style-type: none"> - Target was not visible, only a dark and formless surface. - Filled, diamond-shaped target that looked exactly like the example pictures of the stimuli. - Form of the target could not be identified; only a non-geometric, black surface was visible. The form differed; sometimes only a short blinking was visible.
4. Bright Target	<ul style="list-style-type: none"> - Black mask with a white target. - In the white star a white diamond was visible. - White diamond with a black border.
5. No Target	<ul style="list-style-type: none"> - No awareness of the target, but only of the mask. - Impression is as if the mask was presented twice; target is not perceived. - Target could not be perceived, it was only a brief flash. Impression is as if something was presented but it cannot be described.
6. Rotation	<ul style="list-style-type: none"> - I had the impression of two pictures following each other. Because of this, the border of the mask rotates and a movement results. This impression refers only to the mask. The target was not visible, neither as form nor as black patch. - There was rotation in the transition from target to mask. - Two different forms create a motion in the sequence; it seems as if the picture is rotating.
7. Expansion	<ul style="list-style-type: none"> - At first, the target was small in the middle of the star of the mask and then grew in size to the border of the mask. At first only the target was visible; afterwards the mask and then both together were visible. - A small, black point starts to grow in the middle of the fixation point and trails the white part of the star of the mask behind it. It is an angular expansion oriented on the shape of a diamond or square. - Expansion occurred if target and masked had the same shape. Or, the impression of a non-geometrical, dark spot expanding towards the border of the mask.
8. Other	<ul style="list-style-type: none"> - Mask was good to see, but very quickly gone. - Star looks bigger and the frame of the mask smaller; the tips of the star seem to be cut off. - Mask looks plastic, as if it had been stuck on a ball. - Order was reversed; target stimulus was visible after the mask, like an afterimage. There was nothing to be perceived before the mask. - Target and mask overlapped. The mask had more corners because the target overlapped the mask. The target was hardly perceived, with only its corners protruding beyond the mask.

Table 1. Exemplary idiosyncratic descriptions of different participants for each percept-category (translated from German).

Category	Cohen's κ		
	Experiment 1a	Experiment 1b	Pooled experiments
Target inside mask	0.27	0.37	0.35
Target before mask	0.21	0.58	0.51
Dark target	0.76	0.61	0.67
Bright target	0.48	0.65	0.62
No target	0.82	0.72	0.76
Rotation	1.00	0.76	0.85
Expansion	0.66	0.96	0.90
Overall κ , mean (SD)	0.6 (0.29)	0.66 (0.18)	0.67 (0.19)

Table 2. Inter-rater reliability of Experiment 1a and Experiment 1b for each percept category.

	Congruency		Linear SOA		Quadratic SOA		Congruency × linear SOA		Congruency × quadratic SOA	
	Rater 1	Rater 2	Rater 1	Rater 2	Rater 1	Rater 2	Rater 1	Rater 2	Rater 1	Rater 2
Target inside mask	0.03	0.46	0.21	0.09	0.35	0.21	0.58	0.37	0.22	0.02
Target before mask	0.006	0.50	0.33	0.15	0.16	0.025	0.002	0.079	0.006	0.019
Dark target	0.13	0.11	0.54	0.83	0.13	0.03	0.08	0.25	0.82	0.90
Bright target	0.24	0.44	1	0.49	0.80	0.71	0.007	0.55	0.098	0.57
No target	0.98	0.78	0.71	0.38	0.001	0.001	0.30	0.26	0.58	0.79
Rotation	0.001	0.001	0.001	0.002	0.007	0.012	0.001	0.0004	0.008	0.008
Expansion	0.04	0.08	0.04	0.03	0.31	0.20	0.15	0.07	0.45	0.66

Table 3. The p values for each effect of the randomization test, calculated separately for rater 1 and rater 2. Effects are considered significant when, for both raters, $p < 0.05$ (indicated in bold).

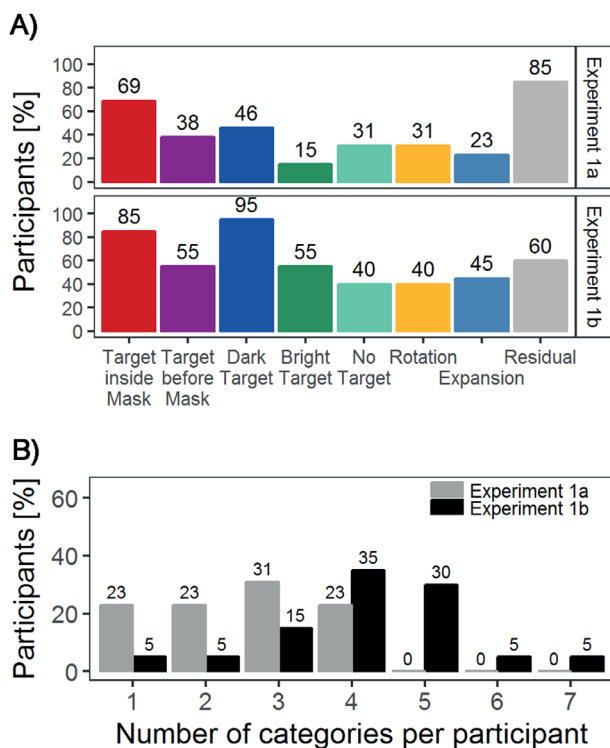


Figure 2. Classification of spontaneous descriptions in Experiment 1 based on rater 1. (A) Percentage of participants, whose spontaneous descriptions in the training phase were classified into the respective percept categories in Experiment 1a (top) and Experiment 1b (bottom). (B) Percentages of participants whose spontaneous descriptions in the training phase were classified into the respective number of seven percept categories (without the residual category Other) for Experiment 1a (gray bars) and Experiment 1b (black bars).

Visual inspection of reports of target inside mask suggests a decreasing trend with SOA, but no effect proved significant for both raters (main effect of congruency, $p = 0.03$ for rater 1; interaction of congruency × quadratic trend of SOA, $p = 0.02$; all

other, $p > 0.09$). Target before mask seemed to be reported more often with increasing SOA, especially with incongruent target–mask pairs, which is partially confirmed by a significant interaction of congruency × quadratic trend of SOA ($p = 0.018$) and a marginally significant interaction of congruency × linear trend of SOA ($p = 0.002$ for rater 1 and $p = 0.078$ for rater 2). No other effect reached significance (all $p > 0.15$).

Dark Target was reported very often but did not show significant relations with congruency or SOA for both raters (quadratic trend of SOA, $p = 0.03$ for rater 2; all other, $p > 0.08$). The percept category Bright Target showed the expected decreasing frequency across SOA, at least according to rater 1, but these effects did not prove significant (interaction congruency × linear trend of SOA, $p = 0.007$ for rater 1; all other, $p > 0.09$; all $p > 0.44$ for rater 2). No Target was reported predominantly at intermediate SOAs, which is corroborated by a significant inverse quadratic trend of SOA ($p = 0.001$). All other effects were not significant (all $p > 0.25$).

Participants reported Rotation almost only on incongruent trials with an increasing frequency of reports with increasing SOA. This effect was corroborated by a resampling test that yielded a main effect for congruency ($p = 0.0012$), increasing trends of SOA ($p = 0.0016$ and $p = 0.012$ for linear and quadratic trends, respectively), and interactions of congruency with both trends ($p = 0.001$ and $p = 0.008$ for linear and quadratic trends, respectively). Expansion reports were marginally more frequent on congruent than on incongruent trials ($p = 0.08$) and decreased linearly with increasing SOA ($p = 0.03$). No other effect reached significance (all $p > 0.14$).

Discussion

Experiment 1 provided a first insight into the phenomenology of a metacontrast masking paradigm.

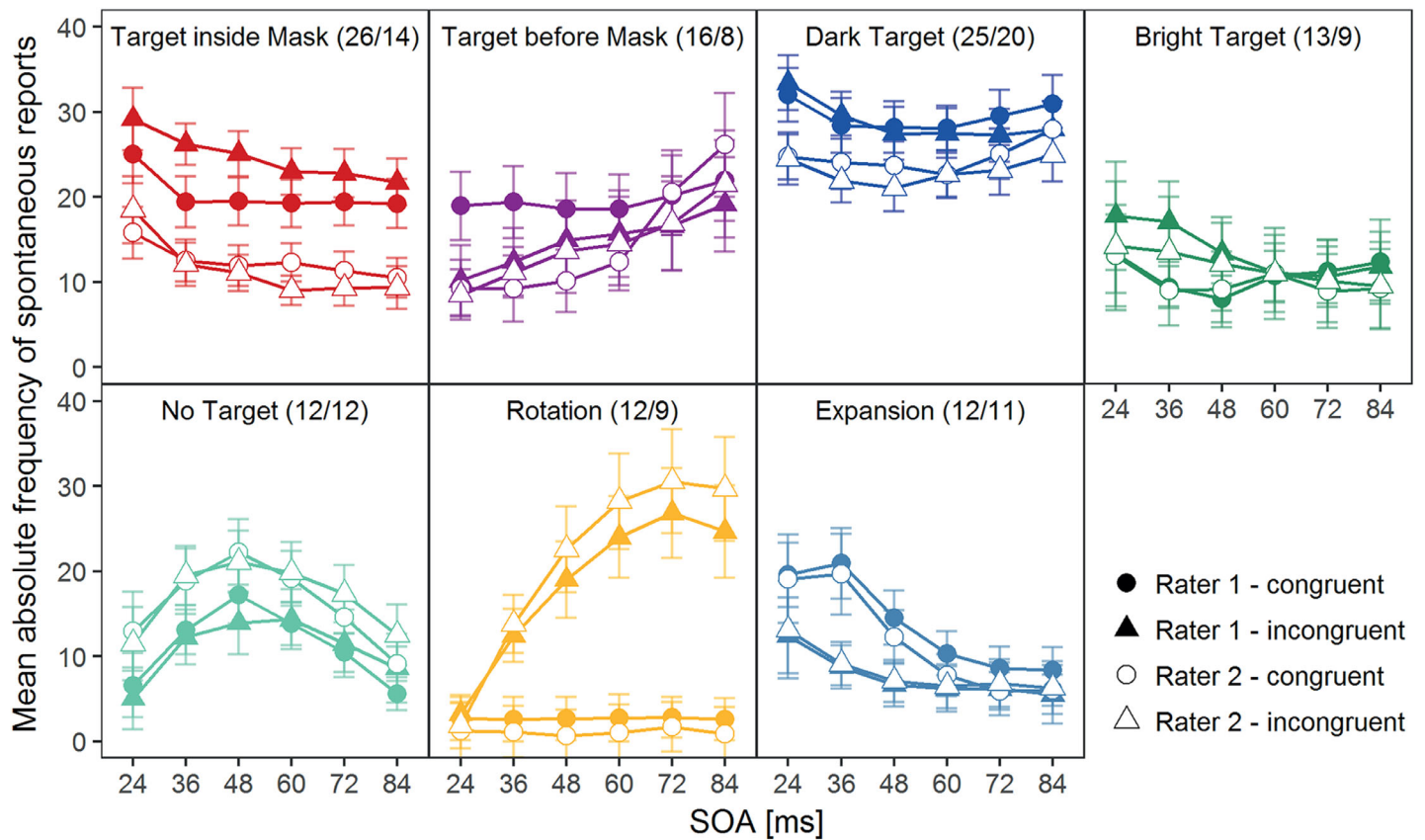


Figure 3. Mean absolute frequencies of classified reports in the test phase of [Experiment 1](#) for each of the seven percept categories as a function of SOA and congruency. Error bars depict within-subject standard error ([Loftus & Masson, 1994](#)). Numbers in brackets indicate the number of participants on which each perceptual category is based (rater 1/rater 2). Maximum number of trials was $N = 56$. The absolute number of participants was 33.

The main results are straightforward: Even under the sparse stimulation conditions of metacontrast, $\sim 89\%$ of all participants spontaneously reported rich and detailed visual experiences, which occurred repeatedly on different trials. These idiosyncratic descriptions were similar across participants and were related to (1) the perceived temporal order of target and mask (percepts Target inside Mask and Target before Mask); (2) the perceived contrast of the target (Dark Target, Bright Target, and No Target); and (3) motion percepts (Expansion and Rotation). Percepts matching all seven percept categories were reported on a substantial number of trials, although the number of reports varied widely among categories and participants. The inter-rater reliabilities were moderate to high except for the time-related percept categories. These findings suggest that metacontrast induces a multidimensional experience of the target stimulus and challenges approaches that attempt to capture the visual experience of target stimuli in metacontrast with global one-dimensional scales. Moreover, results provide evidence that SOA and congruency modulate the frequencies of the different percepts differentially. This

finding accords well with previous reports indicating that different perceptual aspects of the metacontrast sequence follow different masking functions (e.g. [Ansorge et al., 2009](#); [Kahneman, 1967](#); [Neumann & Scharlau, 2007](#); [Reeves, 1982](#); [Weisstein & Grownay, 1969](#)).

The two percepts that reflect the temporal sequence of events (Target inside Mask and Target before Mask) were modulated by SOA in the predicted way, with more frequent reports of an integrated percept (Target inside Mask) with short SOAs and more frequent reports of separated events (Target before Mask) with long SOAs. However, this effect was weak, which is possibly due to the low inter-rater reliability of both percepts. We speculate that participants' spontaneous descriptions of their percepts did not differentiate with high precision between a temporal separation, which is critical for the percept Target before Mask, and a spatial separation, which is an important aspect for the percept Target inside Mask. As a consequence, raters might have misclassified the corresponding idiosyncratic descriptions, which might have resulted in mixing these two temporal categories.

Report frequencies of the percepts Dark Target and Bright Target did not vary much with SOA. The report frequency of a dark target was on a high level irrespective of SOA. Because the percept categories were non-exclusive in [Experiment 1](#), it may be that participants perceived the dark target within the mask with short SOAs but before the mask with longer SOAs. The percept Bright Target did not vary systematically with SOA, which may at least partially be caused by the overall low frequency of reports. This finding adds to previous evidence that a brightness reversal seems to be a rather weak or instable phenomenon that may occur only under certain conditions. Consistent with this, [Stewart et al. \(2011\)](#) found brightness reversal only in a spatial forced-choice task, not in a temporal forced-choice task.

In contrast, the inverted U-shaped function found for reports of No Target corresponds to the typical U-shaped type-B-making function commonly found with metacontrast masking (e.g., [Breitmeyer & Öğmen, 2006](#); [Kahneman, 1967](#); [Weisstein & Growney, 1969](#)). This finding confirms the effectiveness of our masking procedure. Whereas discrimination tasks can only evidence the lack of information necessary to infer the shape of the target stimulus, the No Target reports provide direct evidence that the stimuli used in the present study and various previous studies ([Albrecht et al., 2010](#); [Albrecht & Mattler, 2012a, 2012b, 2016](#)) in fact produce strong masking without any visual experience of the target.

The percept Rotation was hypothesized as being helpful for discriminating congruent from incongruent trials with long SOAs, a strategy supposedly leading to a type-A masking function ([Albrecht et al., 2010](#); [Albrecht & Mattler, 2012a, 2016](#)). Our present results show that the frequency of reports of Rotation in fact increases on incongruent trials with increasing SOA. The second motion-related percept, Expansion, was predominantly reported with short SOAs, and the frequency of reports decreased with increasing SOA. Participants described the Expansion as the impression of a target growing in size, for example, as a small spot, which started in the center of the mask and expanded outwards until it fitted into the inner contour of the mask. Therefore, the percept Expansion is probably not associated with an apparent motion between the target and mask as reported previously ([Albrecht & Mattler, 2012](#); [Kahneman, 1967](#); [Weisstein & Growney, 1969](#)). Instead, the percept of expansion might be related to the phenomenon that [Breitmeyer and Jacob \(2012\)](#) called “filling out.”

In sum, the frequency of spontaneous reports of specific percepts varied in a systematic way when SOA and congruency varied. This validates the current approach of investigating the phenomenological space even under starkly reduced stimulation conditions

of visual masking. However, the time courses for the different percepts, especially the rather small SOA effects for some percepts, have to be interpreted with caution because of the limited statistical power of the phenomenological approach. First, some categories, such as Bright Target, are based on the reports of a small number of participants. Second, the idiosyncratic descriptions show a high degree of inter-individual variability that is neglected by categorizing these descriptions into percept categories by the raters, leading to variance within each category and to a low inter-rater reliability. Third, the percept categories are far from being exhaustive as reflected by the high number of reports in the Other category. This suggests that the percept categories do not cover the complete range of visual experiences. Fourth, participants differ in their ability to report percepts verbally, and they differ in their perceptual sensitivity to perceive very subtle visual differences. Accordingly, it is difficult to infer from the absence of a report whether a participant in fact did not experience a specific percept or whether that participant just did not verbalize the experience of this percept. In spite of these limitations, the present approach provides ample evidence for the reliability of the different percepts that occur within a metacontrast paradigm. Findings provide direct evidence that the phenomenology of a target stimulus is not constant across conditions in a metacontrast paradigm. Results demonstrate that spontaneous reports of naïve participants can be used to examine the richness of conscious visual perception by distinguishing various perceptual aspects with moderate reliability.

Note that we varied SOA in the range between 24 ms and 84 ms, which is typical for metacontrast studies. Within this range, the mask has been shown to reduce target visibility across all SOAs (e.g., [Albrecht et al., 2010](#); [Breitmeyer et al., 2006](#); for a review, see [Breitmeyer & Öğmen, 2006](#)). Therefore, we think that the subjective experiences reported by our participants occurred in conditions of proper masking. To ensure this assertion, in [Experiment 2](#) we compared participants' subjective experiences with their performance in an objective target discrimination task, which is typically used in masking studies to measure target awareness.

Experiment 2

The aim of [Experiment 2](#) was threefold: First, we wanted to examine whether individual differences in phenomenological reports reflect individually different phenomenological experiences. Second, we sought to scrutinize the time courses, which we

found in [Experiment 1](#) by employing more powerful statistical analyses. Third, we wanted to clarify how phenomenological differences found in [Experiment 1](#) relate to differences in objective target discrimination performance ([Albrecht et al., 2010](#); [Albrecht & Mattler, 2012a, 2016](#); [Maksimov et al., 2011](#)), which is a more common measure in masking paradigms. In particular, it is of interest whether specific percepts are associated with target discrimination performance at specific SOAs. Note that this approach is similar to the traditional dissociation paradigm testing dissociations between direct and indirect measures of masked primes (e.g., [Reingold & Merikle, 1988](#); [Schmidt & Vorberg, 2006](#); [Vorberg et al., 2003](#)). However, instead of relating one indirect measure (usually the response time difference of incongruent and congruent conditions) to one direct measure (prime shape discrimination performance), we relate two direct measures (subjective reports of target experience vs. objective target shape discrimination performance). To this end, we employed a more rigorous experimental procedure in [Experiment 2](#) by asking participants whether they perceive a specific percept on a given trial and conducted an objective discrimination task in a final session.

Methods

Participants

A group of 25 naïve students (17 female and 8 male; age from 18 to 30 years [$\text{mean} \pm \text{SD} = 22.8 \pm 3.2$ years]) participated in eight sessions of 60 to 90 minutes. One participant was excluded because she could not describe the stipulated percepts corresponding to the instruction in the first session. All participants were from Georg-August University Göttingen, had normal or corrected-to-normal vision, and received a monetary reward. All participants were naïve with regard to the aim of the study and never had participated in a metacontrast masking experiment before.

Tasks

For the subjective reports, in Sessions 1 to 7, participants had to indicate their phenomenological experience of the target-mask sequence in a yes/no task. On each trial, they affirmed or negated the experience of a specific percept by button press. The percept that had to be reported changed between blocks of trials (Target inside Mask, Target before Task, Dark Target, Bright Target, No Target, Rotation, Expansion). We instructed participants as carefully and thoroughly as possible. We informed them about the shapes of target and mask stimuli and their spatial relationship (i.e., the target fit neatly into the inner contours of the mask).

Note that we did not inform participants that SOA was manipulated as an independent variable nor that stimulation conditions did not vary between blocks. We emphasized and acknowledged the difficulty of the task. We explained to the participants that we were interested in whether they experienced the stipulated subjective percepts and that there was no correct or incorrect response option.

For the objective task, in Session 8, participants performed a commonly used objective target discrimination task. They were instructed to respond as accurately as possible and without speed stress to the shape of the target stimuli (diamond vs. square) with a button press of the left or right hand, respectively. For detailed instructions, see Supplementary Information.

Stimuli, procedure, and design

Stimuli, trial sequence, and design were identical to those for [Experiment 1](#) ([Figure 1](#)) with the following exceptions: In addition to SOA and the congruency between target and mask, which were varied within experimental blocks, we varied the perceptual category that participants had to report in a blockwise fashion. In each block of trials, we assessed the participants' subjective experience of one of the seven percept categories: Target inside Mask, Target before Mask, Dark Target, Bright Target, No Target, Rotation, and Expansion. The order of the categories varied pseudorandomly across sessions for each participant so that the order was counterbalanced within participants. At the beginning of each block, a short description of the percept category was presented on the screen to remind the participants what percept they had to report in the following block (see Supplementary Information for details).

Session 1 served as a training session to familiarize participants with the task and the percept categories. It consisted of one warm-up block of 8 trials and 14 blocks of 24 trials each. Each of the congruency \times SOA combinations occurred once per block. In the middle and at the end of each block we requested participants to describe the appearance of a percept of the respective category in their own words. The experimenter repeated this description or corrected it if the description of the participant indicated that the participant had misunderstood the percept category. If participants reported that they did not perceive the stipulated percept category, they were asked to describe their understanding of the percept category to ensure that there was no misunderstanding of the definition of the percept category. The experimenter stayed in the room for the entire first session.

At the beginning of Sessions 2 to 7, participants verbally described the seven percept-categories in their own words and performed one warm-up block of 8 trials followed by 14 experimental blocks of 52

trials each. The first four trials of each block served as adaptation trials for the category of this block and were excluded from all analyses. The levels of the independent variables target, mask, and SOA used in these adaptation trials were balanced across sessions for each percept. Each of the 24 stimulus conditions (2 target \times 2 mask \times 6 SOA) occurred twice in each block. Across six sessions, we collected 48 trials per experimental condition (6 SOA \times 2 congruency \times 7 category) for the analysis of subjective data. This amounts to 576 trials for each percept category (see Supplementary Information for more details). At the end of each block, participants indicated the category they had responded to in the last block so that we were able to control whether they had responded to the stipulated category.

The final session included 12 blocks of 48 trials each. Each of the 24 stimulus conditions occurred twice in each block. Altogether 48 trials per experimental condition (6 SOA \times 2 congruency) were included in the analysis. Participants received no error feedback. Response mapping was counterbalanced across participants and both tasks (subjective and objective).

Data analysis

Subjective data: Data from Sessions 2 to 7 were pooled and included in the analysis. To examine the effect of SOA and congruency, we calculated a generalized linear mixed-effects regression model with a logit link function separately for each perceptual category (package *lme4*; Bates, Mächler, Bolker, & Walker, 2015). The relative frequency of “seen” reports served as a dependent variable. Models included subject as a random intercept, and SOA and congruency as by-subject random slopes to satisfy the assumption of independence (Baayen, Davidson, & Bates, 2008). Fixed effects were congruency (dummy-coded 2-level factor), SOA as metric linear predictor, SOA as metric quadratic predictor, and the interaction between congruency and both terms of SOA. Both SOA terms were scaled to mean = 0 and $SD = 1$. We selected the best model using an automatic backward selection procedure. We started with the full model and iteratively excluded the effect with the largest $p \geq 0.05$ that was not part of any significant higher-order effect. Model selection stopped when all remaining effects had $p < 0.05$ or were part of a higher-order interaction (see Panis & Schmidt, 2016). The final model was tested against the full model by a log-likelihood test.

Objective data: Discrimination performance in Session 8 was assessed by signal detection analysis in terms of discrimination sensitivity, d' (Macmillan & Creelman, 1991). To avoid confounds with response bias we calculated d' separately for each mask and then averaged d' -values across mask (Vorberg, Mattler, Heinecke, Schmidt & Schwarzbach, 2004). Hit rate and false alarm

rates were corrected according to the log-linear rule to avoid infinite values of d' (Hautus, 1995). We analyzed the effect of SOA on d' by fitting linear mixed-effects models (function *lmer*, package *lme4*). Models included subject as random intercept and SOA as linear as well as quadratic fixed effects. To control for individual differences in the slope of masking functions (Albrecht et al., 2010) models included SOA additionally as random slope. All SOA variables were scaled to mean = 0 and $SD = 1$.

Subjective versus objective data: In a final step, we investigated the relationship between subjective reports and objective data for each percept category separately. To this end, we included the subjective data of the percept category that we gathered in Sessions 2 to 7 (i.e., the relative frequencies of yes reports at each SOA) as an additional predictor variable into the linear mixed-effects model of objective discrimination data. To keep the models as parsimonious as possible, we averaged the relative frequencies across congruency except for the percept category Rotation, for which we used the difference between report frequencies on incongruent and congruent trials as the predictor. For these seven separate analyses, we used Bonferroni-corrected alpha levels of $\alpha = 0.007$. Additional t -tests based on percentages where conducted with arc-sin-transformed data.

Results

Subjective data

Figure 4 depicts the percentage of affirmative reports for each percept category pooled across congruency and SOA. It shows substantial variability across categories (horizontal lines) and participants (points). Retest reliabilities were determined by correlating the frequency of reports on Sessions 2 to 4 with reports on Sessions 5 to 7. Reliabilities for the categories were acceptable to high (Target inside Mask: $r = 0.77$, $p < 0.001$; Target before Mask: $r = 0.88$, $p < 0.001$; Dark Target: $r = 0.86$, $p < 0.001$; Bright Target: $r = 0.95$, $p < 0.001$; No Target: $r = 0.75$, $p < 0.001$; Rotation: $r = 0.91$, $p < 0.001$; Expansion: $r = 0.84$, $p < 0.001$).

Figure 5 depicts the time courses of the percent of affirmative reports across SOA and congruency for each category. Table 4 summarizes the results of the generalized linear mixed effect models for each percept-category. For Target inside Mask, the final model included a negative linear and a positive quadratic trend of SOA, indicating a curvilinear decrease of frequencies of yes reports with increasing SOA. In addition, the main effect of congruency and the interaction Congruency \times linear SOA proved significant, indicating a stronger linear decrease across SOA on incongruent trials. This model

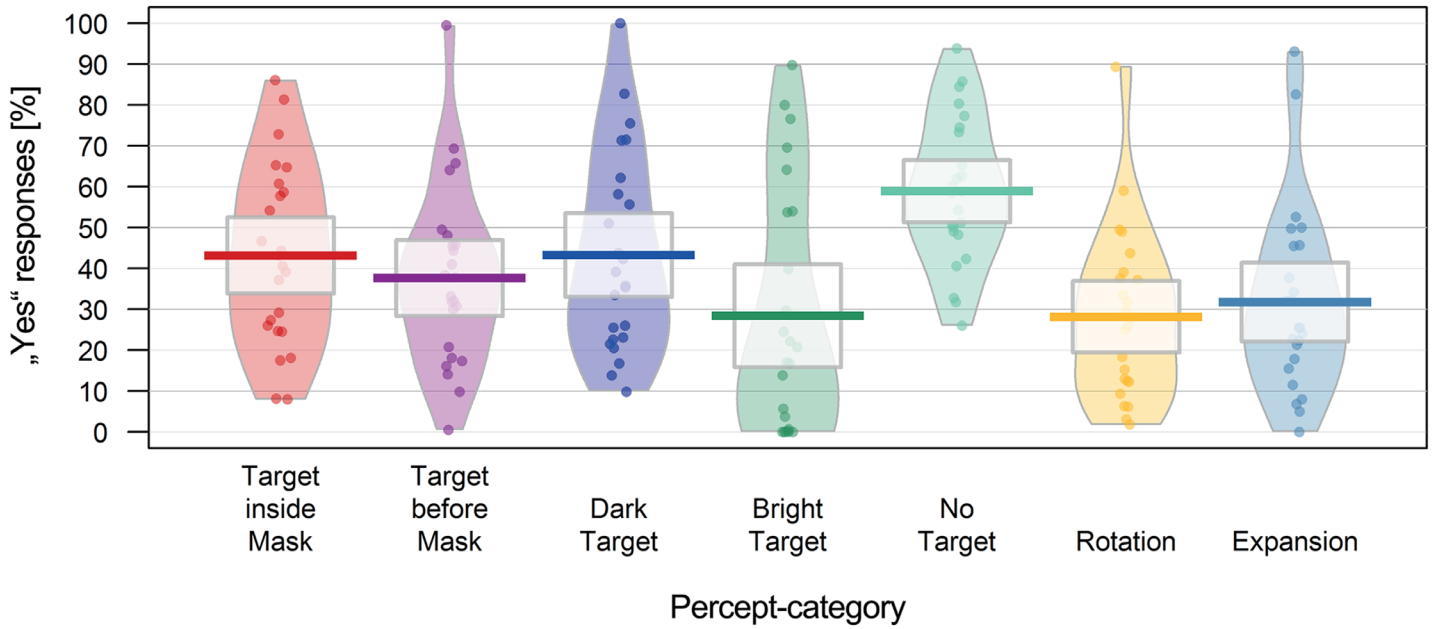


Figure 4. Percentages of trials in which participants reported to perceive a specific percept category in Experiment 2 (“yes” responses); 100% refers to the total number of trials in each percept category ($N = 576$), and points represent the data of single participants. Lines and boxes represent the mean percentage averaged across participants and its 95% confidence interval, respectively. Shaded areas represent the density distribution of reports within each category. On each trial, participants were asked for only one of the seven percepts. The percept that we asked for varied blockwise.

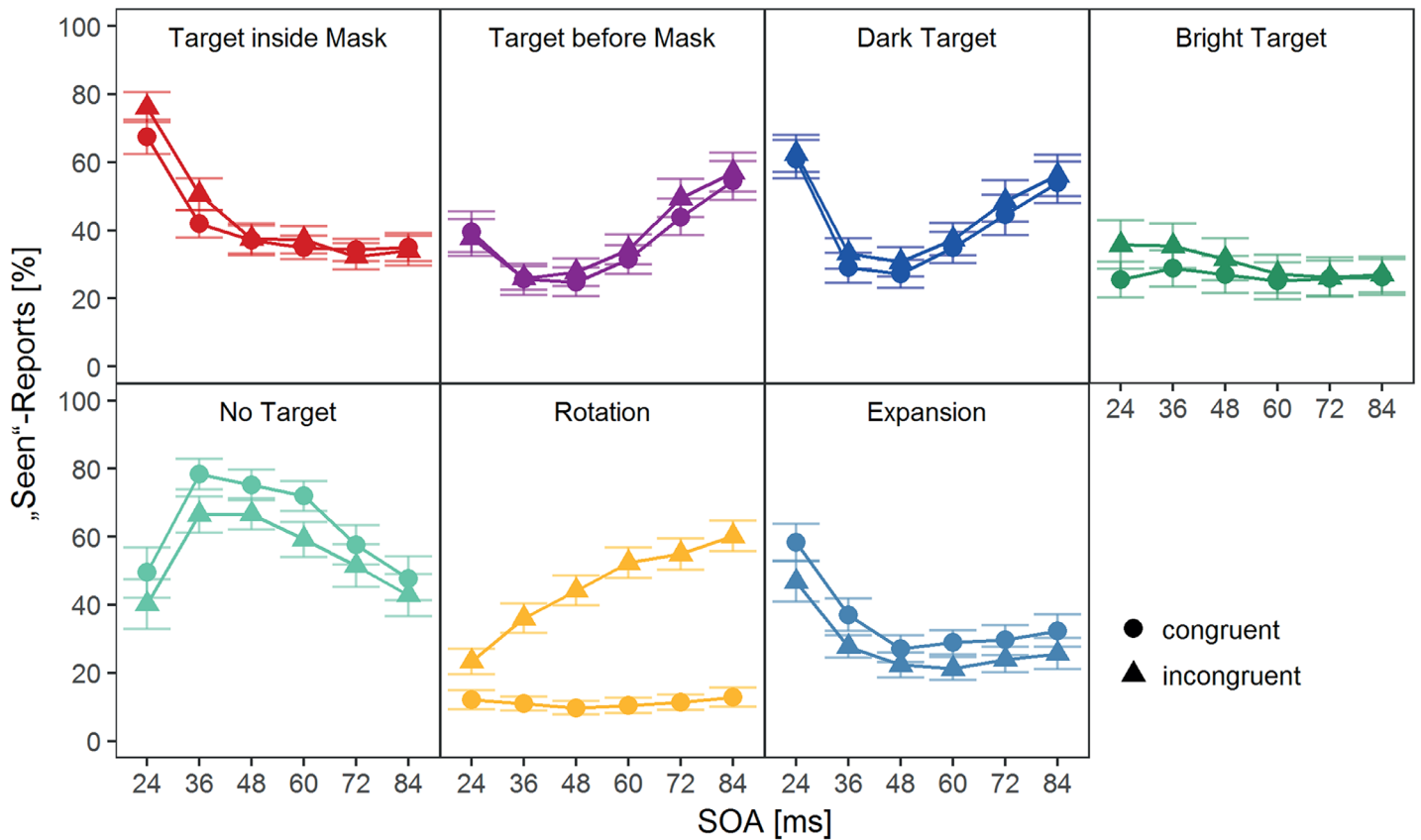


Figure 5. Mean percentages of “seen”-reports as a function of SOA, congruency, and percept category in Experiment 2. Error bars depict within-subject standard error (Loftus & Masson, 1994).

	<i>B</i>	<i>SE</i>	<i>z</i>	<i>Odds ratio</i>	<i>p</i> -value
1. Target inside Mask					
Random effects: Subject ($\sigma = 1.79$), SOA ($\sigma = 0.41$), Congruency ($\sigma = 0.19$)					
Congruent vs incongruent	0.20	0.10	1.97	1.22	.05
SOA as linear predictor	−0.54	0.13	−3.99	0.58	<.001
SOA as quadratic predictor	0.48	0.03	18.50	1.61	<.001
Congruent vs incongruent * SOA as linear predictor	−0.23	0.04	−5.21	0.80	<.001
2. Target before Mask					
Random effects: Subject: $\sigma = 3.55$, SOA ($\sigma = 0.89$), Congruency ($\sigma = 0.23$)					
SOA as linear predictor	0.45	0.20	2.29	1.56	.02
SOA as quadratic predictor	0.48	0.03	17.86	1.62	<.001
3. Dark Target					
Random effects: Subject ($\sigma = 3.09$), SOA ($\sigma = 0.78$), Congruency ($\sigma = 0.02$)					
Congruent vs incongruent	0.20	0.05	3.73	1.22	<.001
SOA as quadratic predictor	0.79	0.03	28.46	2.20	<.001
4. Bright Target					
Random effects: Subject ($\sigma = 17.06$), SOA ($\sigma = 1.57$), Congruency ($\sigma = 0.24$)					
Congruent vs incongruent	0.23	0.18	1.27	1.26	.21
SOA as linear predictor	−0.74	0.30	−2.44	0.48	.01
Congruent vs incongruent * SOA as linear predictor	−0.25	0.05	−4.57	0.78	<.001
5. No Target					
Random effects: Subject: $\sigma = 1.25$, SOA ($\sigma = 0.70$), Congruency ($\sigma = 0.43$)					
Congruent vs incongruent	−0.52	0.14	−3.67	0.60	<.001
SOA as linear predictor	−0.22	0.17	−1.26	0.80	.21
SOA as quadratic predictor	−0.63	0.03	−24.90	0.53	<.001
Congruent vs incongruent * SOA as linear predictor	0.09	0.04	2.13	1.10	.03
6. Rotation					
Random effects: Subject ($\sigma = 3.93$), SOA ($\sigma = 0.15$), Congruency ($\sigma = 0.85$)					
Congruent vs incongruent	3.27	0.23	14.40	26.21	<.001
SOA as linear predictor	0.19	0.10	1.96	1.21	.05
SOA as quadratic predictor	0.12	0.05	2.21	1.13	.03
Congruent vs incongruent * SOA as linear predictor	0.59	0.06	9.50	1.80	<.001
Congruent vs incongruent * SOA as quadratic predictor	−0.36	0.07	−5.57	0.69	<.001
7. Expansion					
Random effects: Subject ($\sigma = 3.33$), SOA ($\sigma = 0.50$), Congruency ($\sigma = 0.82$)					
Congruent vs incongruent	−0.51	0.20	−2.60	0.60	.009
SOA as linear predictor	−0.49	0.15	−3.34	0.61	<.001
SOA as quadratic predictor	0.47	0.03	16.62	1.59	<.001

Table 4. Summary of the generalized linear mixed effect models for each percept-category in Experiment 2 (N = 24, total number of observations: 13824).

did not differ significantly from the full model, as indicated by a log-likelihood test ($X^2(1) = 1.87, p = 0.17$).

For Target before Mask, the final model included only the linear and quadratic effects of SOA. The log-likelihood test indicated a marginally worse model fit compared to the full model ($X^2(3) = 7.48, p = 0.06$). Frequencies of yes reports increased with increasing SOA in a curvilinear fashion. Note that, contrary to

our hypothesis, yes reports were given more often with 24-ms than with 36-ms SOA.

For Dark Target, the final model included the quadratic effect of SOA and the main effect for congruency. This model did not differ significantly from the full model ($X^2(3) = 0.69, p = 0.88$). Yes report frequencies were higher on incongruent than congruent trials and followed a U-shaped function across SOA.

For Bright Target, the final model included the main effect of congruency, the linear effect of SOA, and the interaction congruency \times linear SOA ($X^2(2) = 0.51$, $p = 0.78$). The frequency of yes reports decreased linearly with increasing SOA, especially on incongruent trials. The main effect of congruency did not reach significance.

For No Target, the final model was marginally worse than the full model ($X^2(1) = 3.37$, $p = 0.07$). It included linear and quadratic effects of SOA, congruency, and the interaction congruency \times linear SOA. Yes report frequencies of No Target followed an inverted U-shaped function across SOAs as indicated by a significant negative quadratic trend of SOA. In addition, No Target was affirmed more often on congruent than on incongruent trials together with a slight linear increase of yes reports with increasing SOA on incongruent trials.

For Rotation, the full model could not be reduced. Although the main effect of linear SOA did not reach significance, both the linear and the quadratic effects of SOA interacted significantly with congruency, indicating a strong curvilinear increase of report frequencies with increasing SOA on incongruent but not on congruent trials.

For Expansion, the final model included only the main effects of congruency, linear SOA, and quadratic SOA ($X^2(2) = 3.24$, $p = 0.20$). In accordance with our hypothesis, a negative linear effect of SOA was found, as well as a positive quadratic effect of SOA. The main effect of congruency indicates that the percept Expansion was affirmed more often on congruent than incongruent trials.

Comparing Figure 3 and Figure 5 shows that the time courses of reports for each percept in Experiment 2 correspond well with the time courses of the spontaneous reports given by participants in Experiment 1. To test this more formally, we normalized the relative frequency of reports within each percept and congruency condition to $M = 0$ and computed the correlation between Experiment 1 and Experiment 2 separately for each percept. The scatterplot in Figure 6 shows substantial correlations between both experiments for all percepts ranging from $r = 0.67$ ($p = 0.02$) for Target before Mask to $r = 0.97$ ($p < 0.0001$) for Rotation.

Objective data

On average, discrimination performance decreases with increasing SOA in a curvilinear manner (Figure 7A). This is corroborated by a linear mixed-effects model, which shows a significant negative linear effect of SOA ($\beta = -0.45$; $t(23) = -4.63$, $p < 0.001$) and a significant positive quadratic effect of SOA ($\beta = 0.33$; $t(23) = 8.07$, $p < 0.0001$). For complete model statistics

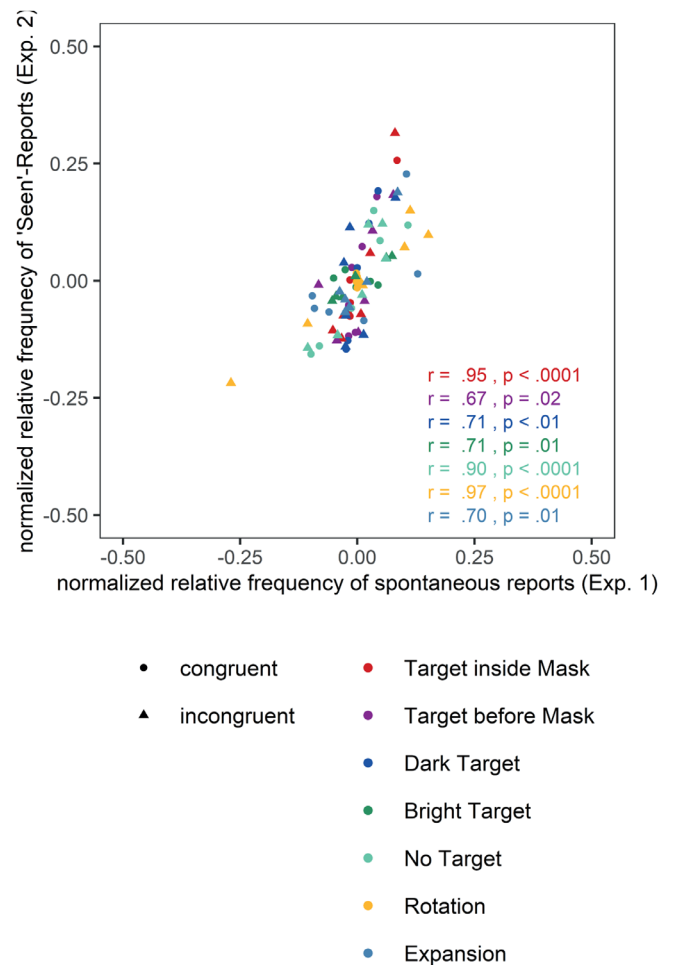


Figure 6. Relation of the time courses of reports across SOA in Experiment 1 (x-axis) and Experiment 2 (y-axis) shows close correspondence for all percepts. Relative frequency of reports are normalized to $M = 0$ for each percept category and congruency condition so that effects of congruency and differences between percepts are diminished. Data from Experiment 1 are based on rater 1. For data based on Rater 2, see Supplementary Figure S2.

see Supplementary Table S1. Visual inspection of the individual discrimination performance (Figures 7B–7F) reveals substantial interindividual differences in the shape and the absolute level of masking functions. For most participants masking functions decrease (Figures 7B–7D), but some participants show U-shaped or increasing masking functions (Figures 7E–7F). For data on response bias C, see Supplementary Figure S4.

Comparing the time courses of the mean objective performance (Figure 7A) and the mean percentage of subjective reports (Figure 5) reveals that the time courses of the percepts Target inside Mask, Bright Target, and Expansion parallel the time course of d' in the objective target discrimination task. In contrast, frequencies of yes reports for Target before Mask,

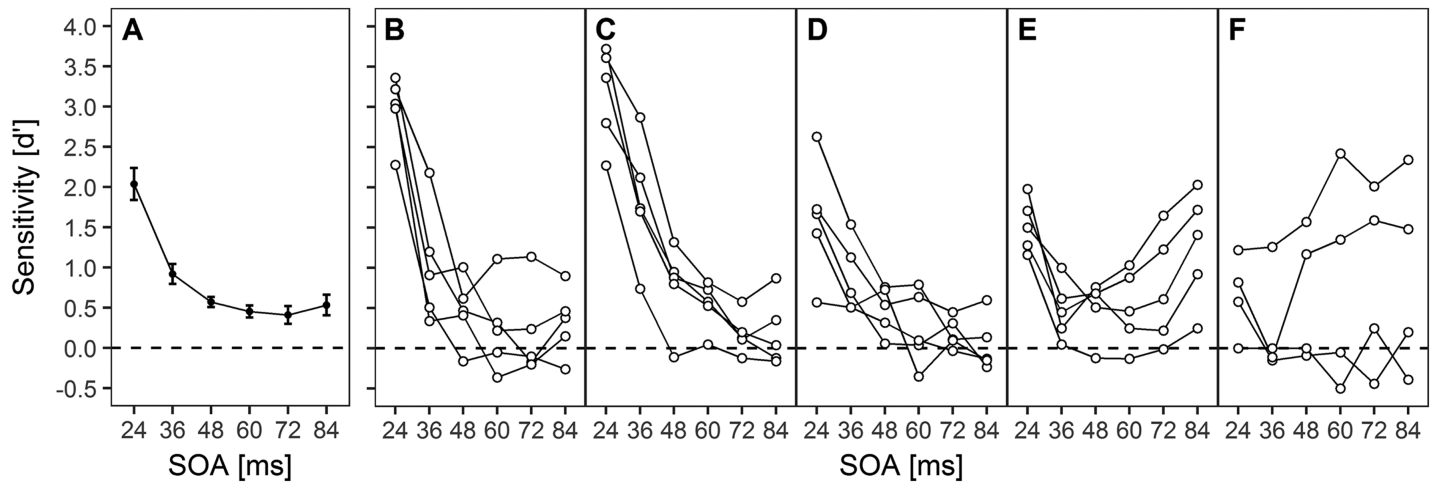


Figure 7. Performance in the objective discrimination task in [Experiment 2](#). Averaged across all participants, performance decreases with increasing SOA (A). Individual masking functions show decreasing courses (B–D), U-shaped courses (E), and flat-line or increasing courses (F).

Dark Target, and Rotation increase with SOA, and the yes report frequencies of No Target decrease with increasing SOA. These latter reports of subjective percepts constitute a double dissociation between subjective and objective measures. Double dissociations occur when the manipulation of one independent variable (SOA) leads to a decrease in one dependent variable (e.g., objective task) and simultaneously to an increase in a second independent variable (e.g., subjective task). This is of great importance because double dissociations are regarded to be strong empirical evidence for an independence of two variables (e.g., [Schmidt & Vorberg, 2006](#)). Participants' performance on the objective task decreases with increasing SOA, although subjective reports indicate that information regarding the temporal succession of the target and mask (Target before Mask), the target by itself (Dark Target, No Target), and the spatial relation of the target and mask (Rotation) increases with increasing SOA. In other words, findings suggest that the information that is associated with these subjectively experienced percepts is not sufficient or is not effectively used to discriminate the shape of the target in the objective task.

One interesting observation regards the comparison of the discrimination performance and the No Target reports at the shortest and at the longest SOA. Affirmative No Target reports did not differ significantly between long and short SOAs, with 55.2% and 54.7% with 24-ms and 84-ms SOAs, respectively ($t(23) = -0.03, p = 0.98$). In contrast, however, objective discrimination performance decreased from 80.2% ($d' = 2.04$) to 58.7% ($d' = 0.53$) with 24-ms and 84-ms SOAs, respectively ($t(23) = 4.87, p < 0.0001$). Moreover, the decrease in objective discrimination performance is significantly stronger, than the decrease in the frequency

of the subjective data ($t(23) = 3.03, p < 0.01$). Although subjectively the same amount of information about the presence of the target is available with short and long SOAs, participants have access to valid information for the objective task only with short but not with long SOAs.

To examine the correlation between subjective data and discrimination performance, for each category we added the frequencies of yes reports as predictor variables to the linear mixed effects model of discrimination performance reported above. Note that the effects of SOA did not change by including additional terms. Therefore, we report only the effects of the percept categories (for detailed information on the models and statistics, see Supplementary Table S2).

For Target inside Mask, frequencies of yes reports yielded a significant interaction with linear SOA ($\beta = -0.19, t(57.59) = -3.37, p = 0.001$), but no main effect nor an interaction with quadratic SOA ($t(63.75) = 2.70, p = 0.009$ and $t(52.07) = 2.32, p = 0.02$, respectively). This finding suggests a positive correlation between subjective experience of Target inside Mask and objective performance in the discrimination task, and this correlation decreases with increasing SOA.

For Target before Mask, Dark Target, and No Target yes report frequencies showed significant main effects on d' values ($\beta = 0.33, t(92.02) = 4.22, p < 0.0001$; $\beta = 0.44, t(89.27) = 6.45, p < 0.0001$, and $\beta = -0.36, t(101.74) = -5.65, p < 0.0001$, respectively). However, there was no significant interaction with linear SOA or quadratic SOA (all $p > 0.10$).

For Bright Target, yes report frequencies showed no significant effect on d' values (all $t < 2.05, p > 0.04$).

For Rotation, yes report frequencies revealed significant interactions with linear SOA ($\beta = 0.18, t(90) = 2.79, p = 0.006$) and quadratic SOA ($\beta = -0.13,$

$t(88.01) = -3.39, p = 0.001$), but no main effect on d' values ($t(89.72) = 0.02, p = 0.98$). This finding indicates a positive correlation between the frequencies of reports of Rotation and d' values, which steeply increases with increasing SOA. For Expansion, yes report frequencies yielded no significant effects on d' values (all $t < 2.00, p > 0.05$).

Discussion

Experiment 2 revealed four important points. First, participants' affirmative responses to the stipulated percepts show high inter-individual variability and a high degree of intra-individual stability across sessions. Across all participants, the reports of the seven percepts show distinct time courses across SOA and correspond surprisingly well with spontaneous reports of the same percepts given by participants in **Experiment 1**. Second, results for the objective discrimination task replicated typical interindividual differences in masking functions (Albrecht et al., 2010, Albrecht & Mattler, 2012, 2016; Maksimov et al., 2011), although all participants became highly practiced in perceiving the stimuli in the first seven sessions. The finding that discrimination performance is substantially impaired for SOAs between 36 ms and 84 ms demonstrates that the subjective experiences of all seven percepts occur under conditions of proper masking. Third, we found a double dissociation between subjective and objective measures because target discrimination performance decreased with increasing SOA, whereas yes reports regarding the percepts Target before Mask, Dark Target, No Target, and Rotation increased. Finally, we found various relations between participants' report frequencies of subjective percepts Target inside Mask, Target before Mask, Dark Target, No Target, and Rotation and their objective target discrimination performance. In the following, we discuss the seven percepts in detail.

Percepts related to perceived temporal order

The two percepts Target inside Mask and Target before Mask showed the expected decreasing and increasing time courses across SOA, respectively, corroborating earlier findings on the perceived temporal order of target and mask (Neumann & Scharlau, 2007; Reeves, 1982). Our data provide new evidence for the general view that the frequency of an integrated percept of target and mask decreases and the frequency of two segregated events increases when SOA increases. In detail, however, our data deviate from previous findings by showing a slightly increased frequency of Target before Mask with the shortest SOA compared to intermediate SOAs.

There are at least two possible explanations for this deviating result. First, participants might mix up the two percepts with short SOAs because it is too difficult to differentiate between segregated and integrated percepts. In former studies on the perception of temporal order under metacontrast (Neumann & Scharlau, 2007; Reeves, 1982) participants were forced to choose between “integrated” or “segregated” responses on each trial, whereas we assessed both percepts independently in different blocks. This may lead to a higher probability to affirm either category in cases where participants perceive a dark target. Second, depending on the exact stimulation parameters, the human visual system is able to differentiate two events in time that are only 10 to 50 ms apart (e.g., Lewis, 1968; Samaha & Postle, 2015). Therefore, chances are that even with 24-ms SOA, the target and mask can be perceived as successive stimuli at least on some trials. In this case, however, one would expect a monotonic increase of report frequency with increasing SOA. Instead, our data show a decrease in frequency with intermediated SOAs, so this explanation seems unlikely, although it may be speculated that a masking process that impedes the experience of the target stimulus at intermediate SOAs also prevents the perception of successive events.

The time course of the frequency of yes reports regarding Target inside Mask closely parallels the time course of the performance in the objective target discrimination task. In line with this finding, our analysis of discrimination performance as a function of SOA and subjective report showed that participants who more frequently reported the integrated percept at short SOAs also showed better discrimination performance at short SOAs. We interpret this finding as evidence that the integrated perception of the target inside the mask is used as a valid cue in the target discrimination task. In contrast, the frequency of yes reports regarding Target before Mask dissociates from objective performance at longer SOAs, suggesting that information about the presence of the target as discrete stimulus increases with SOA, but that this information is not sufficient to solve the objective target discrimination task. Nevertheless, the individual tendency to report a segregated percept is positively correlated with discrimination performance.

Percepts related to target contrast

The frequency of yes reports regarding the percept of Dark Target and No Target shows pronounced U-shaped and inverted U-shaped time courses, respectively, corresponding to typical type-B masking functions that has been found with luminance rating tasks (e.g., Breitmeyer et al., 2006; Neumann & Scharlau, 2007) and subjective rating tasks using the perceptual awareness scale (PAS) (Overgaard et al.,

2006; Sandberg et al., 2010; Sandberg et al., 2011).

This result is in accordance with the assumption of maximum metacontrast suppression at intermediate SOAs (Kahneman, 1967; Weisstein & Growney, 1969) and strengthens the validity of the present approach.

Yes reports regarding the No Target percept reached 80% with intermediate SOAs and approximately 30% with the shortest and longest SOA of our study. Thus, with intermediate SOAs participants had little information about the presence of the target, suggesting that only sparse information about any target aspect was accessible in these conditions. With shorter and longer SOAs, more information about the presence of the target is accessible. However, although this information suffices to report the presence of a target, it differs in quality depending on SOA because, despite similar frequencies of No Target reports with short and long SOAs, target discrimination performance was higher with short than with long SOAs. This indicates that the information at the long SOAs suffices to detect the target but it is not sufficient to discriminate between target shapes.

The percept Bright Target refers to the metacontrast literature in which several authors reported not only the phenomenon of a suppression of target contrast but also a phenomenon of brightness reversal (e.g., Stewart et al., 2011; Werner, 1935). Our results contribute to and extend these findings by showing a low but reliable frequency of yes reports regarding the percept Bright Target, which declines with increasing SOA. The fact that a Bright Target is reported predominantly with short SOAs corresponds to Stewart et al. (2011), who found evidence for brightness reversal with 20-ms SOA. Note, however, that there are several differences between our study and the study of Stewart et al. (2011). First, we presented only one target and one mask at fixation, whereas Stewart and colleagues presented one target disc either left or right from fixation followed by two masks on the corresponding positions left and right of fixation. Second, we asked participants directly about their subjective visual experience, whereas participants of Stewart et al. (2011) decided on which side the target disc had been presented. In such an indirect task, it is not entirely clear what criterion content participants use (e.g., contrast/luminance, flicker). Therefore, it remains unclear how the percept Bright Target that participants affirmed in our study is related to the evidence for brightness reversal reported by Stewart et al. (2011). In any case, our data suggest that Bright Target is a reliable percept that is experienced by instructed observers. However, the frequency of affirmative reports did not correlate with participant's performance in the objective target discrimination task. This negative outcome strongly suggests that the afterimage, which we have described to be a reliable cue for target discrimination in earlier studies (Albrecht & Mattler, 2012a), does not correspond to a brightness reversal.

Percepts related to motion

The percept-categories Rotation and Expansion are related to motion. The time courses across SOA of the frequencies of yes reports regarding these stipulated percepts were in accordance with the time courses of spontaneous reports in Experiment 1. Rotation was reported almost exclusively on incongruent trials and predominantly with long SOAs (Albrecht & Mattler, 2012a, 2012b; Maksimov et al., 2011). Frequency of yes reports for Expansion showed a decreasing time course across SOA. This finding was unexpected because studies on apparent motion show a peak of apparent motion perceptions with intermediate SOAs (Hogben & Di Lollo, 1984; Kahneman, 1967; Weisstein & Growney, 1969). This literature describes the percept of an expansion as the impression of an objectless enlargement, which occurs even at maximum metacontrast suppression. In contrast, in the present study participants described the phenomenology of Expansion as a growing object within the mask. In the debriefing, 21 participants sketched an Expansion as a movement in the center of the mask, and eight of them described perceiving a target growing in the center of the mask.

To sum up, the two motion-related percepts differ in their time courses as well as in their phenomenology. Therefore, it seems unlikely that these two percepts are based on a common mechanism of apparent motion. The phenomenological description of Expansion in terms of a target that grows in size, resembles the description of phenomena that were related to processes contributing to surface completion (Breitmeyer & Jacob, 2012). Breitmeyer and Jacob (2012) examined the temporal dynamics of filling-out processes in metacontrast masking paradigms. These authors assumed different temporal dynamics in surface and contour completion which could produce percepts with degraded contrasts at the edges of a target compared to the center of the target (Petry, 1978; Werner, 1935). Breitmeyer and Jacob (2012) showed that surface completion is progressing with increasing SOA until the target is perceived entirely with long SOAs. Against the background of the proposal of Breitmeyer and Jacob (2012), our data suggest that filling-out processes might cause the motion-related percept Expansion, which is more often perceived with short SOAs but remains at a low frequency across the entire range of SOAs. This seems plausible, as filling-out might produce stronger motion signals with short SOAs than with long SOAs, where surface completion reaches its end.

General discussion

The present study provides a systematic investigation of a broad range of phenomenological experiences

in a metacontrast paradigm. Results show that naïve participants spontaneously describe rich and detailed visual experiences comprised of temporal aspects of the target and mask, contrast-related aspects, and motion-related aspects. The distinct time courses across SOA can be linked to existing metacontrast research. These findings validate our phenomenological approach and provide evidence that participants are able to reliably describe their manifold phenomenological experiences.

These findings support the idea that each percept represents a unique experience of a different aspect of the target, whose appearance does not just reflect a trial-by-trial fluctuation in perception but instead depends on specific stimulus conditions. Findings exemplify the richness of visual phenomenology by demonstrating that human observers can experience seven different percepts under identical stimulus conditions, which is remarkable considering the simplicity of the spatial layout of the stimuli. Results provide evidence for the view that the experience of a target stimulus varies not only quantitatively but also qualitatively with varying stimulus conditions in a metacontrast masking paradigm (Jannati & Di Lollo, 2012; Sackur, 2013).

The systematic and replicable variations of the reported frequencies across SOA and congruency are compelling evidence against the assumption that the subjective impression of a rich and detailed representation of the world is simply based on perceptual illusions (Kouider et al., 2010). Instead, the experience of subtle differences in a difficult perceptual task, which varies gradually with the parametric manipulation, speaks in favor of the trustworthiness of subjective reports. With this study, we introduce an approach to assess the phenomenology in an experimental setting that promises to avoid the problems of former introspective approaches from the beginning of the 20th century which often either failed to confirm their hypotheses (Vermersch, 1999) or lacked successful replications (Velmans, 2007). For each of the seven percepts, our approach produced meaningful patterns of results in two samples of participants which can be accommodated in the metacontrast literature. Therefore, we think our approach might contribute to the rehabilitation of phenomenological research in cognitive psychology, which has previously been condemned as unreliable (Nisbett & Wilson, 1977).

Multidimensionality of target appearance

The various dissociations between the subjective measures, as well as the dissociations from the objective target discrimination performance, are surprising and consequential. With long SOAs, we found poor target discrimination performance and concurrently rich

subjective experiences of the target. This dissociation points to the fact that the critical information to discriminate the target shape in the objective task bears on a small part of the broad range of subjective experiences. This demonstrates that the richness of the phenomenological experience of the target stimulus cannot be captured by one-dimensional measures of awareness (e.g., discrimination performance or global visibility ratings).

Beyond this, however, we found that the different subjective measures are mutually dissociated from each other, indicating that subjective experience has to be conceived as a multidimensional pattern of experiences. It is important to note that this finding casts doubt on all attempts to measure visual awareness in a single univariate measure because some other aspects of visual experience might always vary in opposite ways across a given parameter such as SOA. In consequence, the idea of an exhaustive measure or a gold standard for measuring consciousness appears simplistic. Any approach to measure visual experience exhaustively has to face the challenge of capturing a multivariate pattern of visual experiences because there might always be some subjective measure that is dissociated from the measure at hand (Reingold & Merikle, 1988). In this perspective, subjective and objective measures are not fundamentally different but refer to different stimulus dimensions that result from specific tasks. They differ mainly because objective measures can be classified as correct or incorrect in relation to the actual stimulus, whereas subjective measures are always interpreted as correct because participants propose that they experience what they report. In principal, however, the data in an objective task could be analyzed as a subjective measure if the correct/incorrect distinction is ignored given a suitable instruction. In this case, when the subject has to indicate the shape of the target (e.g., square vs. diamond), the response of the subject might be construed as subjective measure (“square” or “diamond”). Under this premise, the validity of objective measures of consciousness is not fundamentally different from the validity of subjective measures of consciousness.

The multidimensional pattern of visual experiences also presents a challenge to the traditional dissociation paradigm. This paradigm attempts to show that masked primes can have indirect effects that dissociate from direct measures of the prime. This dissociation can be construed as evidence for the processing of unconscious information (e.g., Reingold & Merikle, 1988; Vorberg et al., 2003). The multidimensional structure of visual experience emphasizes the need to measure appropriate aspects of phenomenological experience that are relevant to the indirect effects of the prime (e.g., Reingold & Merikle, 1988; Schmidt & Vorberg, 2006). First, the ability to detect the presence of a masked prime, for example, might remain

compatible with an interpretation of a dissociation so long as the prime discrimination performance and the priming effect do not co-vary along a modulating variable (e.g., Vorberg et al., 2003). Second, the absence of a correlation between direct and indirect effect is not sufficient in cases where the direct effect is based on a dimension of the prime that is irrelevant for the indirect effect. Third, the possibility arises that discrimination performance might correlate with priming effects, although participants cannot truly discriminate the relevant aspect of the prime when they choose an aspect of the visual experience as criterion content that is irrelevant for priming but serves to solve the direct task (Dienes & Seth, 2010b). For example, participants may use the presence or absence of a rotation to infer the shape of the prime without seeing the prime (Albrecht & Mattler, 2012a). In this case, discrimination performance increases with SOA in the same manner as the priming effect (Albrecht et al., 2010). Therefore, our findings call for a careful examination of participants' behavior in dissociation paradigms.

Moreover, multidimensionality provides boundary conditions for theory building. Just like the scales for measuring awareness, theoretical approaches to metacontrast masking must take this multidimensionality into account. Models that focus on only one dimension or predict only global “target visibility” are difficult to reconcile with the current findings. A full-fledged model for metacontrast masking should be able to simulate different masking functions for different dimensions. The current RECOD model is one approach in this direction (Breitmeyer et al., 2006; Breitmeyer & Öğmen, 2006). This model provides an account for different masking functions for contour and surface information, but it does not cover the entire range of percepts. On the other hand, the perceptual retouch model (Bachmann, 1984, 1994; Kirt & Bachmann, 2013) is most compatible with the broad range of percepts in metacontrast masking. This model assumes that information about a stimulus is conveyed by two different pathways. The specific pathway is comprised of cortical neural networks that process the perceptual content of a stimulus. The unspecific pathway is comprised of a subcortical route that conveys delayed stimulus activity, which “raises” the particular perceptual content into consciousness. Although this model allows for a broad range of different percepts, it does not relate the parameters of the stimulation to specific percepts.

Individual differences

Despite identical stimulation conditions, participants show stable and qualitative performance differences in the objective target-discrimination task. For some

participants, performance decreases with increasing SOA; for others, performance increases (Albrecht et al., 2010). This phenomenon has been replicated multiple times in our own lab (Albrecht & Mattler, 2012a, 2012b, 2016; Fleischhauer, Miller, Enge, & Albrecht, 2014), as well as by others (e.g., Maksimov et al., 2011). We have linked these differences to differences in the visual experience of the target mask sequence (Albrecht & Mattler, 2012) and to differences in the weighting of underlying processes (Albrecht & Mattler, 2016). In particular, we proposed one process that leads to the perception of an afterimage of the target inside the mask with short SOAs and one process that leads to the perception of apparent (rotational) motion with long SOAs (Albrecht et al., 2010; Albrecht & Mattler, 2012a, 2016).

The present study provides additional evidence for the link between subjective percepts and objective performance. First, participants differed widely in their reported visual experiences in free report (Experiment 1a) and in a yes/no decision task (Experiment 2). Therefore, these differences cannot be attributed to differences in verbalization or verbal abilities.

Second, our analysis regarding the relation of subjective data and objective performance in Experiment 2 showed that individual discrimination performance was higher for participants who frequently reported perceiving Dark Target and Target inside Mask, but it was not related to the frequency of reports of Bright Target. Therefore, we conclude that the afterimage mentioned in our earlier studies (e.g., Albrecht & Mattler, 2012a) is probably a persisting image of the target that may be caused by mechanisms of visual persistence rather than a negative afterimage related to the percept Bright Target.

Third, in Experiment 2, individual discrimination performance with long SOAs was higher for participants who frequently reported Dark Target, Target before Mask, and Rotation with these SOAs. However, although almost all participants reported Rotation with long SOAs, average discrimination performance was low at long SOAs for most participants. This dissociation indicates that participants perceived a rotation but did not use this cue to discriminate the target. This corroborates our earlier finding that not only did participants differ in the ability to perceive specific perceptual cues, but they also differed in the degree to which they exploited these cues in the objective target discrimination task (Albrecht & Mattler, 2012a).

Fourth, the visual experience of a Bright Target or an Expansion possibly does not provide information regarding the shape of the target. These percepts may reflect processes that underlie metacontrast masking but that do not affect the processing of the target shape because neither the frequency of reports of Bright

Target nor the frequency of reports of Expansion related to objective performance. In sum, we have identified a series of percepts that are reported with individually different frequencies. Moreover, these percepts have the potential to be used as cues in target discrimination tasks, but participants seem to differ in the extent to which they use these cues. We consider these percepts as candidates reflecting different underlying processes that contribute to the shape of individually different masking functions (Albrecht & Mattler, 2016).

Perceptual learning

Perceptual learning refers to the improvement in the performance on a perceptual task by practice (Ahissar & Hochstein, 2004). It is widely known that perceptual learning affects the performance in metacontrast masking (Albrecht et al., 2010; Hogben & Di Lollo, 1984; Schwiedrzik, Singer, & Melloni, 2009; Ventura, 1980). In the studies of Ventura (1980) and Hogben and Di Lollo (1984), practice led to a flattening of the U-shaped masking function due to decreased masking at intermediate SOAs. The authors explained this effect by a change in criterion content; that is, participants changed the perceptual cue on which they based their judgment and gradually learned to utilize it over the course of the experiment.

In contrast, Albrecht et al. (2010) showed that individual masking functions became more and more pronounced as practice increased. They explained their findings in the framework of reversed hierarchy theory (Ahissar & Hochstein, 2004). In a first learning phase, a reliable perceptual cue is identified. In a second phase, perceptual learning leads to more and more efficient utilization of this specific cue. Depending on the exact nature of the cue, participants develop either a masking function that increases with SOA (type A) or a masking function that decreases with increasing SOA or shows a U-shaped masking function (type B).

Schwiedrzik et al. (2009) found that practice in discriminating the shape of targets in metacontrast masking not only improved the discrimination performance but also improved subjective awareness ratings on a perceptual awareness scale. Thus, subjective awareness was influenced by training in an objective task. In the present study, participants practiced their subjective awareness of different percepts that emerged within the target mask sequence and performed a discrimination task afterward. Does this extensive practice in subjective awareness (over seven sessions of 1 hour or more) affect performance in the objective task? Because we have not gathered pretraining data of objective performance, we cannot draw final conclusions. However, we do not see any sign of substantial perceptual learning effects. The

average masking function is clearly type B, and most participants showed low discrimination performance with long SOAs. Nevertheless, almost all participants reported a rich visual experience of the target with long SOAs, including the percepts of Dark Target, Target before Mask, and Rotation. Thus, although participants were aware of perceptual cues that could help to discriminate the target at long SOAs, only a few participants utilized these cues. Other participants did not or could not use these cues. On the one hand, one could argue that the reported subjective percepts did not include information about the shape of the target so that learning to see a specific percept cannot lead to improved shape discrimination. On the other hand, however, our data show that participants who were more prone to see a dark target before the mask were better in the discrimination task. In addition, at least the cue which results from the percept Rotation can in principle be utilized in the discrimination task (e.g., Albrecht & Mattler, 2012a). In this regard, our results confirm and extend earlier findings of a dissociation between the ability to see a certain perceptual cue and the ability to utilize this cue (Albrecht & Mattler, 2012a). Future research is needed to examine whether perceptual learning affects only specific and individually preferred percepts.

Limitations

Two limitations of the current study have to be mentioned. First, the restricted SOA range between 24 ms and 84 ms may have resulted in low variability in visual experience and therefore may have increased the difficulty of the task. This context might have influenced the characteristics of the percepts in the present study. Therefore, percepts might change their characteristics when the range of SOA changes. For example, the time course of the report frequency of Target before Mask might increase more steeply if longer SOAs are employed. However, despite the restricted SOA range, we found reliable effects of SOA in all categories, validating our conclusions despite this limitation.

Second, we analyzed the different percepts strictly independent from one another, but we do not claim that percepts are in fact independent from one another. We rather suspect that they are not. The fact that some of the idiosyncratic descriptions given in Experiment 1 contained more than one perceptual category may be interpreted as a sign for dependency, but based on the present data we cannot draw conclusions. Current research in our lab investigates the dependencies between percepts to achieve a more detailed picture of the phenomenology.

Third, we only used a certain type of stimuli—square and diamond targets and masks, which formed either

congruent or incongruent pairs on each trial. Therefore, we do not claim that participants would experience exactly the same percepts with the same frequency if stimuli were changed. For example, our data show that the experience of rotation is limited to the occurrence of incongruent stimulus pairs. In addition, it is likely that stimulus features, such as the shape, contrast polarity, and size of stimuli, also affect the type of percepts that occur, as these factors are known to influence the masking function (e.g., Bridgeman & Leff, 1979; Duangudom, Francis & Herzog, 2007; for a review, see Breitmeyer & Ögmen, 2006). However, although we cannot generalize our specific results to any other metacontrast stimuli, our general and most important point remains unaffected by this limitation: Within the same paradigm, participants experience different and varying aspects of the target, which vary across SOA and dissociate in multiple ways from each other and from objective discrimination performance. This is clear evidence that one-dimensional and global measures of awareness (e.g., post-decision wagering, perceptual awareness scales, discrimination tasks, detection tasks) can never be exhaustive and that the use of such scales as the gold standard must be critically questioned.

Conclusion

We developed a new approach to examine the phenomenological experience of simple visual stimuli that takes into account requirements of naturalized phenomenology to overcome the limitations of previous phenomenological approaches. We applied this approach to investigate the richness of phenomenological experience in a metacontrast masking paradigm with simple stimuli. First, we collected spontaneous reports of percepts of naïve observers who were only trained to focus on the target stimulus in the metacontrast sequence. The frequency of reports of individual percepts was systematically modulated by the experimental variables SOA and congruency. Second, we had naïve raters classify the individual descriptions of the percepts into seven percept categories that we found in a scattered literature on metacontrast. Third, we trained a new sample of participants to report the appearance of each of the seven percepts and observed how the frequency of reports of each percept varied with SOA and congruency. The correspondence between the characteristics of the spontaneous and the instructed reports indicates that we are reliably measuring specific stable entities and thus validates our approach, although these entities are subjective experiences that vary considerably among participants. The

comparison of the characteristics of the percepts with the characteristics of similar reports in the literature revealed that our approach produces meaningful results. Findings provide evidence for the view that phenomenal consciousness forms a multidimensional pattern that is not reducible to a single measure. This multidimensionality has far-reaching implications: First, any measure of consciousness that claims to be exhaustive has to capture a multivariate pattern of visual experiences, which cannot be done by single one-dimensional subjective or objective scales. Second, any approach to demonstrate a dissociation between indirect and direct effects of masked primes has to consider carefully, which dimension of the multivariate pattern is the most relevant. Third, multidimensionality provides new boundary conditions for theory building. A comprehensive model of masking must allow for multiple visual experiences and must be able to explain different masking time courses for multiple stimulus dimensions.

Keywords: consciousness, phenomenology, subjective reports, visual masking, metacontrast

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