Activation of response force by self-splitting objects: Where are the limits of feedforward Gestalt processing?

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Most objects can be recognized easily even when they are partly occluded. This also holds when several overlapping objects share the same surface features (self-splitting objects) which is an illustration of the grouping principle of Good Gestalt. We employed outline and filled contour stimuli in a primed flanker task to test whether the processing of self-splitting objects is in accordance with a simple feedforward model. We obtained priming effects in response time and response force for both types of stimuli, even when increasing the number of occluders up to three. The results for outline contours were in full accordance with a feedforward account. This was not the case for the results for filled contours (i.e., for self-splitting objects), especially under conditions of strong occlusion. We conclude that the implementation of the Good Gestalt principle is fast but still based on recurrent processing.

Introduction

Visual object perception relies on the process of perceptual grouping by which the visual system binds together elements and features within a scene. Perceptual grouping occurs according to grouping principles, as described by the Gestalt school of perceptual psychology in the early 1900s (e.g., Wagemans et al., 2012a; Wertheimer, 1923). However, many of these principles are not yet fully understood with respect to neurophysiology, visual attention, or systematic differences between the principles. In this paper, we study the processing dynamics of the principle of *Good Gestalt* (or *Prägnanz*). We do this by measuring rapid visuomotor responses to occluded shapes because the process by which they are separated from occluding elements relies on Good Gestalt cues.

Good Gestalt and visual completion

The principle of Good Gestalt has been put forward by the Gestalt school in order to encompass several principles of grouping (Koffka, 1935; Wertheimer, 1923). The principle states that within a visual scene, elements are bound together such that the perceived object is as "simple," "regular," and as "well-structured" as possible.[1] In this sense, it subsumes a number of basic grouping principles. *Grouping by connectedness, grouping by proximity, and grouping by good continuation* or *collinearity* (i.e., grouping of elements that are aligned with each other along a smooth path) are well-studied examples. The Good Gestalt principle has specific implications for our perception. A shape or figure (i.e., *Gestalt*) that is perceived as the consequence of Good Gestalt has a perceptual advantage over other parts of the visual scene. For example, it can be more easily distinguished from other objects and extracted as a whole even when it is not fully visible.

This advantage, in turn, links the concept of Good Gestalt tightly to the research on *visual completion*. In this field, investigation focuses on the extent to which humans can perceive objects that are partly occluded. This ability is of immediate and crucial importance for everyday life in which an object is often occluded, either by other objects or by parts of the object itself (Palmer & Ghose, 2008). Indeed, humans are very good at this task and can easily infer invisible object parts based on earlier experiences and general perceptual principles
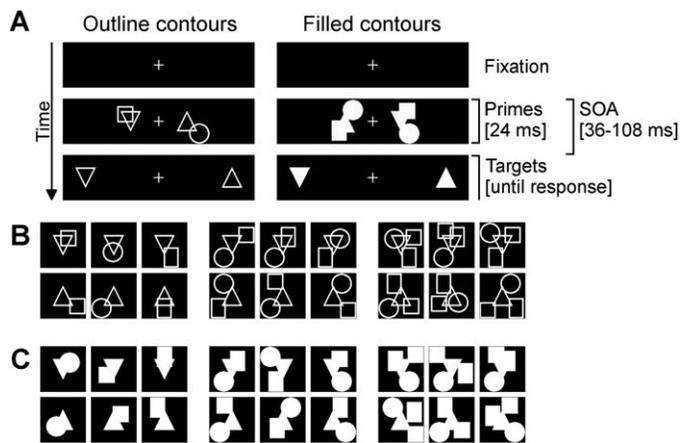
Figure 1. Procedure and stimuli. Two primes and two flanking targets were presented in the sequences displayed (A). Participants were asked to respond to the position of either the upward or downward pointing target triangle. Primes were self-splitting objects containing triangles that were either mapped to the same responses (consistent cases) or opposite responses (inconsistent cases) as the targets. Examples of the outline contour stimuli (B) and filled contour stimuli (C) with an increasing number of occluders (panels from left to right).

(Good Gestalt being one of them; e.g., Dinnerstein & Wertheimer, 1957). The process of visual completion is especially easy for simple shapes (e.g., triangles, rectangles, and circles) because all of them are *Good Gestalten* as defined above.

Self-splitting objects

To understand the process of visual completion or any other visual phenomenon, it is essential to know its time course. Our visual percept changes rapidly over time, and these changes provide valuable information about the cognitive and physiological mechanisms underlying the perceptual process of interest (cf. Hegdé, 2008; T. Schmidt, Haberkamp, Veltkamp, et al., 2011).

In the present paper, we will investigate the time course of a special case of visual completion: that of *self-splitting objects* (Kellman & Shipley, 1991; Petter, 1956). When a new object is created by superimposing several 2-D objects with the same surface features, observers often perceive a configuration of several distinct objects (e.g., when superimposing a white triangle and a white rectangle on a dark background, cf. Figure 1C). This percept at least arises when the objects are not too complex and the observer has had previous experience with them.

In every self-splitting object there are areas where the superimposed 2-D objects overlap and in which, as a consequence, the 2-D objects' physically defined contours have gaps. In our perception, these gaps are spanned by interpolated contours. As a result of our adaptation to a visual environment where no objects are lying in the same depth plane, we perceive the different objects in a certain depth ordering, displaying the so-called Petter's effect: Those contours crossing the smaller gap appear in front while those crossing the larger gap are seen behind (Petter, 1956). This impression results in the nearer contour having illusory contours (*modal completion*) and the farther contour having occluded contours (*amodal completion*).

The mechanisms underlying modal and amodal completion processes are still under debate. The main controversy arises around whether both are separate processes (Anderson, 2007a, 2007b, 2007c), whether both are the result of a common mechanism of object interpolation across gaps (*identity hypothesis*; Kellman, Garrigan, & Shipley, 2005; Kellman, Garrigan, Shipley, & Keane, 2007), or whether both are the result of a common mechanism of surface creation (Kogo & Wagemans, 2013). The origin of the perception of self-splitting objects is even more unclear because it involves both modal and amodal completion processes (*quasi-modal*; Kellman et al., 2005). Nevertheless, because we know that the principle of Good Gestalt plays a major role in the processing of self-splitting objects, it is expedient to use these stimuli to measure the principle's time course and processing characteristics.

The time course of visual completion

Although previous studies did not measure the processing time course of self-splitting objects, they measured that of visual completion through psychophysical methods (e.g., Bruno, Bertamini, & Domini, 1997; Guttman, Sekuler, & Kellman, 2003; Murray, Sekuler, & Bennett, 2001; Ringach & Shapley, 1996; Sekuler & Palmer, 1992) as well as in electrophysiological and imaging studies (e.g., Lerner, Hendler, & Malach, 2002; Sugita, 1999). For example, Guttman et al. (2003) used a *primed-matching technique* in which participants have to indicate as fast as possible whether two simultaneously presented target shapes are the same. This response is known to be faster when a preceding prime shape is identical to the targets. As targets, the authors presented complete shapes (circles or squares) or notched shapes (circles or squares). Primes were either the target shapes or a circle occluded by a square (or a square occluded by a circle) whose contours matched the part missing from the notched targets. First, they observed the standard effect: Responses were faster to complete targets preceded by complete primes and to notched targets preceded by notched primes. Second, and more importantly, they found that responses were faster to complete targets

preceded by notched primes, but only when prime presentation times were longer than about 200–250 ms.

Overall, it has been shown that visual completion develops roughly in the first 50–200 ms after stimulus presentation although the actual results strongly depend on task and stimulus characteristics as well as individual differences. Most prominently, the time to completion is shorter when the amount of occlusion is smaller (e.g., Shore & Enns, 1997). This correspondence led to the formulation of the *Temporal Variation Hypothesis*, stating that the visual system can interpolate a greater amount of occluded information with longer processing times (Guttman et al., 2003). In all probability, this correlation also applies to self-splitting objects: The processing time for separating the shapes that are part of the objects is likely to increase with the number of objects and the amount of overlap between them. To control for this effect, we used objects that were composed of a varying number of shapes.

Measuring the time course of Good Gestalt

In order to determine the processing dynamics of the principle of Good Gestalt, we employed a *primed flanker task* (F. Schmidt & Schmidt, 2013, 2014). This task is a special case of the *response priming paradigm* (Klotz & Neumann, 1999; Klotz & Wolff, 1995; F. Schmidt, Haberkamp, & Schmidt, 2011; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) that is especially useful to investigate early phases of fast visuomotor processing (T. Schmidt, Haberkamp, Veltkamp, et al., 2011).

This paradigm has two advantages over the primed-matching paradigm that was used in previous studies for measuring the time course of visual completion for occluded objects (e.g., by Guttman et al., 2003; for a discussion of the shortcomings of the primed-matching paradigm, see Murray et al., 2001). First, response priming effects are usually large, robust, and not diminished by training. Second, the mechanisms underlying response priming are well understood, and the existing theoretical accounts allow for a classification of the findings with respect to neuronal feedforward versus feedback processing (F. Schmidt, Haberkamp, & Schmidt, 2011; T. Schmidt, Haberkamp, Veltkamp, et al., 2011; T. Schmidt, Niehaus, & Nagel, 2006). In the following, we will describe the task and theoretical background against which we will analyze and interpret our findings.

In response priming, participants react as quickly and accurately as possible to a target stimulus that is preceded by a prime stimulus either mapped to the same response as the target (consistent cases) or to the alternative response (inconsistent cases). Typically, responses are faster and participants make fewer errors in consistent compared to inconsistent configurations. The response priming effect is defined as the difference between response speed or error rates in consistent vs. inconsistent cases, and it increases with the stimulus-onset-asynchrony (SOA) between prime and target presentation.

Response priming effects occur because the prime activates the response assigned to it, as proposed by the *rapid-chase theory* (T. Schmidt et al., 2006; T. Schmidt, Haberkamp, Veltkamp, et al., 2011): Prime and target signals elicit feedforward sweeps of neuronal activation that traverse the visuomotor system in strict sequence, without any temporal overlap (Lamme & Roelfsema, 2000; see Vorberg et al., 2003, for a formal model). The motor response is initiated and driven by the prime signal into either the correct or incorrect direction until the subsequent target signal takes over response control, explaining the increase of priming effects with SOA. By monitoring the earliest motor output in online motor measures such as pointing responses or response force, the properties of such a system can be described in terms of three *rapid-chase criteria*: (a) prime rather than target signals should determine the onset and initial direction of the response (*initiation criterion*); (b) target signals should influence the response before it is completed (*takeover criterion*); (c) movement kinematics should initially depend only on prime characteristics and be independent of all target characteristics (*independence criterion*). An input-output system meeting these criteria is termed a *rapid-chase system* (T. Schmidt et al., 2006; see T. Schmidt, 2014, for formal definitions).

Rapid-chase theory makes strong predictions for response-time distributions of keypress responses as well. It predicts that priming effects in fast responses should be at least as large as those in slower responses (F. Schmidt & Schmidt, 2014; Seydell-Greenwald & Schmidt, 2012). For example, Seydell-Greenwald and Schmidt (2012) asked their participants to respond to the orientation of illusory and real-contour targets that were preceded by illusory and real-contour primes. They found that both target types were primed by illusory contours, and that this effect was fully present in the fastest responses, as expected if illusory contours are able to activate rapid motor responses and are processed in a feedforward manner without time-consuming intracortical feedback. In the same manner, we can use response priming with keypress responses to investigate whether shape targets are primed by simple geometric shapes that are part of self-splitting objects, and if so, whether these priming effects are consistent with feedforward processing of self-splitting contours.

Note that while other feedforward models define feedforward processing in terms of neuronal activity at a microscopic level (e.g., Thorpe, Fize, & Marlot, 1996; VanRullen & Koch, 2003), the rapid-chase definition

works from the functional relationship between sequential input and sequential output of the entire macroscopic system. Therefore, it does not preclude quick local feedback or local recurrent activity (e.g., Bullier, 2004; Roland, 2010) as long as sequential primes and targets still lead to strictly sequential motor outputs. Rapid-chase systems also tolerate different overall speeds of processing for different stimulus properties as long as behavior meets the functional requirements for a rapid-chase process. Therefore, processing does not necessarily have to be extraordinarily fast ("ultra-rapid," VanRullen & Thorpe, 2001) to be considered feedforward, just as raw speed does not guarantee feedforward processing. Thus, the rapid-chase criteria can be used to identify processing that is *behaviorally equivalent* to a feedforward system, even though they cannot guarantee that the system is feedback-free at a microscopic level. However, note that there is currently also no physiological measure that can unanimously identify pure feedforward processing, for example, map complete feedforward pathways (e.g., Roelfsema, Lamme, & Spekreijse, 2004). For the time being, our definition of a feedforward process has the advantage of making strong predictions for overt behavior that can be stated in precise mathematical terms (T. Schmidt, 2014).

In the present study, we wanted to know whether the visual system can extract simple geometric shapes from self-splitting objects in rapid visuomotor processing. Furthermore, we wanted to know whether this already occurs in the earliest (feedforward) phases of processing (F. Schmidt & Schmidt, 2014; Seydell-Greenwald & Schmidt, 2012) and whether it is modulated by the amount of occlusion of the simple shapes. We investigate these questions by analyzing response times (Experiment 1) and response force (Experiment 2) in a response priming task.

Experiment 1

In a primed-flanker task (cf. F. Schmidt & Schmidt, 2013), participants were asked to respond as quickly as possible to the upward or downward pointing of two target triangles that were presented simultaneously in the left and right periphery. Targets were preceded at varying time intervals (SOAs) by one upward- and one downward-pointing prime triangle in the center of the screen whose spatial arrangement could be either consistent or inconsistent with that of the targets (e.g., the upward prime triangle could be on the same side as the upward target triangle or on the opposite one, Figure 1A). Importantly, prime triangles were occluded by one, two, or three other shapes (i.e., square, rectangle, and/or circle) in the same plane and

luminance, increasing the number of interruptions in the primes' visible edges and contours. Primes and targets were either defined by outline contours (Figure 1B) or filled contours (Figure 1C).

Generally, primes should trigger priming effects only if the visual system is able to extract the triangle shapes from the primes. We investigated the capacity of self-splitting objects for priming speeded motor responses and response errors, analyzing the entire response time distributions. By analyzing the earliest motor output of the visuomotor system, we link the results to neuronal feedforward activation. If processing of the self-splitting objects is feedforward, rapid-chase theory predicts priming effects that increase monotonically with prime-target SOA. In addition, it predicts that priming effects should be fully present in the fastest responses and not increase any further for slower responses.

Finally, the number of shapes in the primes was varied to obtain different amounts of occlusion. Previous psychophysical experiments with occluded shapes (e.g., Guttman et al., 2003) as well as with illusory shapes (e.g., Gegenfurtner, Brown, & Rieger, 1997) led us to expect that priming effects would be smaller with more superimposed shapes (cf. *Temporal Variation Hypothesis*). In the same line of argument, outline contours were expected to produce priming effects more easily than filled contours, because the interruptions in their contours are much smaller.

Methods

Participants

Eight right-handed students from the University of Kaiserslautern, Germany (three female, five male, ages 22–24), with normal or corrected vision participated in the experiment for payment of € 6 per hour. All of them provided written informed consent in accordance with the Declaration of Helsinki and were treated in accordance with the ethical guidelines of the American Psychological Association. They were debriefed after the final session.

Apparatus and stimuli

The participants were seated in a dimly lit room in front of a CRT color monitor (1280 × 1024 pixels) with a monitor retrace rate of 85 Hz at a viewing distance of approximately 70 cm.

The stimuli (primes and targets) had either outline contours (line width of 0.09° of visual angle, 1 cm ≈ 0.82° of visual angle; Figure 1B) or filled contours (Figure 1C). Contour type was blocked across sessions, so that all stimuli in a given session were either outline or filled contours. Targets were isosceles triangles (with

a base and height of 1.56°) that pointed upward or downward and were presented in white (60.00 cd/m^2) on a dark background (0.13 cd/m^2). Primes were designed by superimposing one, two, or three occluder shapes (square: 0.90° × 0.90°; rectangle: 0.82° × 1.15°; circle: diameter of 1.15°) on an upward target triangle such that each shape overlapped with the triangle (Figure 1B, C). Every class of primes (one, two, or three occluders) contained 30 stimuli. All primes were generated off-line and each participant was presented with the same stimuli. In the filled-prime contours, the number of occluders determined the number of visible edges (2.13, 1.07, and 0.47, respectively) and the amount of visible contours (66%, 58%, and 42%, respectively) of the prime triangle. All primes in each class were also flipped horizontally to obtain stimuli with downward triangles. Primes and targets were arranged on the left and right side of the fixation cross (diameter of 0.41°; 60.00 cd/m^2) in the center of the screen. The center-to-center distance between fixation cross and prime triangles was about 1.89°, that between fixation cross and target triangles about 3.69°.

Procedure

Typical trials are depicted in Figure 1A. In the beginning a fixation cross was presented. After a variable delay, two primes were presented for 24 ms simultaneously to the left and right of fixation. After an SOA of either 36, 60, 84, or 108 ms, targets appeared to the left and right of the prime positions. In a two-alternative forced choice task, participants had to decide as quickly and accurately as possible on which side of the fixation cross the upward target triangle (half of the participants: downward triangle) was presented. They were instructed to ignore the primes. The two triangles of the primes had always opposite orientations and the two triangles of the targets had always opposite orientations. The number of occluders varied randomly on a trial-by-trial basis between one and three. The two primes in a particular trial always had the same number of occluders. Targets remained on screen until participants gave their response.

The time interval from trial start to target onset was constant at 1000 ms to allow for an optimal preparation for each response to the target. After each block, summary feedback on response times and error rates was provided. All stimulus combinations of consistency, prime-target SOA, and number of occluders occurred equiprobably and pseudo-randomly in a completely crossed repeated-measures design.

Participants responded in six half-hour sessions alternately to either outline contours or filled contours (always two sessions in a row). Each of these consisted of one practice block of 32 trials followed by 27 blocks of 32 trials, accumulating to a total of 5,184 trials per participant.

Data treatment and statistical methods

Practice blocks were not analyzed. For the analysis of response times and error rates, we eliminated trials with response times shorter than 100 ms or longer than 1000 ms (0.02% and 0.02% of trials with outline contours and filled contours, respectively). For the analysis of response time distributions, we *vincentized* response times by sorting them into multiple ordinal bins of data (Ratcliff, 1979), starting from the fastest response times all the way through the slowest ones. Each bin summarized 10% of the cumulative distribution. We did this ranking separately for each participant and condition (defined by the levels of consistency and SOA for the outline and filled contours). As a result, the priming effect can be examined as a function of response speed and SOA. Note that the first and last bins are excluded because they are likely to be distorted by outliers.

We performed repeated-measures analyses of variance (ANOVAs) with Huynh-Feldt-corrected *p* values. ANOVAs for analyzing response times and error rates were fully factorial with factors of consistency (*C*), prime-target SOA (*S*), and number of occluders (*O*). All error rates were arcsine-transformed to comply with ANOVA requirements. ANOVAs for analyzing response time functions had an additional factor of decile (*D*) and we only report results with interactions of consistency and decile. We report all *F* values with subscripts indicating the respective effect (e.g., $F_{C \times S}$ for the interaction of consistency and prime-target SOA).

Results

Response times and error rates: General

The results are depicted in Figure 2. An overall ANOVA including an additional factor of stimulus type (outline contours vs. filled contours; ST) showed response priming effects in response times and error rates, $F_C(1, 7) = 54.44$, $p < 0.001$; $F_C(1, 7) = 42.76$, $p < .001$: Participants responded faster and made fewer errors when prime and target triangles on the same side of fixation had the same orientation. In both measures, this effect increased with prime-target SOA, $F_{C \times S}(3, 21) = 9.03$, $p = 0.001$; $F_{C \times S}(3, 21) = 8.12$, $p = 0.001$ and decreased with the number of occluders, $F_{C \times O}(2, 14) = 5.88$, $p = 0.019$; $F_{C \times O}(2, 14) = 17.04$, $p < 0.001$. Also, overall response times slowed down with the number of occluders, $F_O(2, 14) = 12.64$, $p = 0.001$, while error rates remained constant, $F_O(2, 14) = 0.01$, $p = 0.992$. In general,
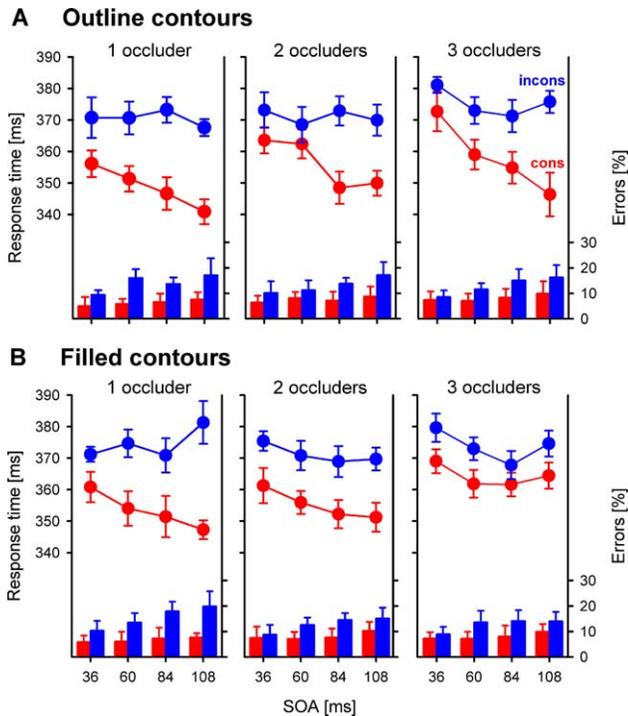
Figure 2. Results of the primed flanker task in Experiment 1 for outline contours (A) and filled contours (B). Mean response times (line plots) and error rates (bar plots) in consistent (red) and inconsistent (blue) trials are displayed as a function of prime-target SOA. Error bars denote the standard error of the mean corrected for between-subjects variance (Cousineau, 2005).

response times and error rates were not different for outline and filled contours, $F_{ST}(1, 7) = 0.11$, $p = 0.750$; $F_{ST}(1, 7) = 0.35$, $p = 0.572$. To investigate these results in more detail, we performed separate analyses for each class of stimuli.

Response times and error rates: Outline contours

With outline contours (Figure 2A), we obtained reliable priming effects in response times and error rates, $F_C(1, 7) = 43.31$, $p < 0.001$; $F_C(1, 7) = 27.66$, $p = 0.001$, that increased with SOA, $F_{C \times S}(2, 14) = 9.03$, $p = 0.001$; $F_{C \times S}(2, 14) = 8.12$, $p = 0.001$. The number of occluders modulated priming effects in error rates, $F_{C \times O}(2, 14) = 4.52$, $p = 0.052$; $F_{C \times S \times O}(6, 42) = 2.55$, $p = 0.034$, but not in response times, $F_{C \times O}(2, 14) = 2.14$, $p = 0.156$; $F_{C \times S \times O}(6, 42) = 0.98$, $p = 0.433$. Specifically, the net priming effect in error rates was larger with one occluder (7.79%) compared to two or three occluders (5.46% and 4.79%). Finally, responses slowed down if the number of occluders increased, $F_O(2, 14) = 8.81$, $p = 0.006$. The total error rate was 10.30% of all trials.
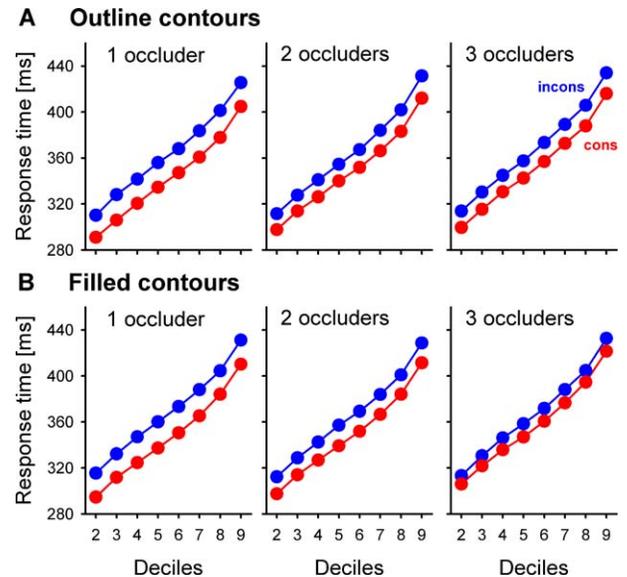

Figure 3. Response time functions in Experiment 1 for outline contours (A) and filled contours (B). Response times in consistent (red) and inconsistent (blue) trials are displayed as a function of response speed (deciles 2 to 9), separately for the different numbers of occluders. It is a strong prediction of rapid-chase theory that priming effects should be fully present in the fastest responses and should not increase any further in slower responses. Data were collapsed across SOA because that factor did not interact with the factor decile.

Response time distributions: Outline contours

The analysis of the response time functions for outline contours revealed priming effects, $F_C(1, 6) = 36.45$, $p = 0.001$, that were not modulated by the factor decile, $F_{C \times D}(7, 42) = 0.62$, $p = 0.499$; $F_{C \times S \times D}(42, 252) = 0.76$, $p = 0.800$; $F_{C \times O \times D}(14, 84) = 0.18$, $p = 0.997$; $F_{C \times S \times O \times D}(42, 252) = 0.84$, $p = 0.681$. In other words, the priming effect was fully developed in the fastest responses and did not change in slower ones (Figure 3A).

Response times and error rates: Filled contours

With filled contours (Figure 2B), we obtained priming effects in response times and error rates, $F_C(1, 7) = 50.11$, $p < 0.001$; $F_C(1, 7) = 33.96$, $p = 0.001$, that increased with SOA in error rates, $F_{C \times S}(2, 14) = 9.80$, $p = 0.001$, but not in response times. The number of occluders strongly modulated priming effects in response times as well as error rates, $F_{C \times O}(2, 14) = 9.12$, $p = 0.003$; $F_{C \times O}(2, 14) = 8.18$, $p = 0.004$. Specifically, in response times the net priming effect linearly decreased with the number of occluders (20.87, 16.25, and 9.68 ms), and in error rates was larger with one occluder (8.74%) compared to two or three occluders (4.62% and 4.55%). Finally, overall responses also slowed down

with the number of occluders, $F_O(2, 14) = 13.31$, $p = 0.001$. The total error rate was 10.58% of all trials.

Response time distributions: Filled contours

Just as with outline contours, we obtained priming effects, $F_C(1, 7) = 51.67$, $p < 0.001$, with filled contours that were not modulated by the factor decile, $F_{C \times D}(7, 49) = 0.73$, $p = 0.504$; $F_{C \times S \times D}(21, 147) = 1.37$, $p = 0.232$; $F_{C \times O \times D}(14, 98) = 0.20$, $p = 0.944$; $F_{C \times S \times O \times D}(42, 294) = 0.68$, $p = 0.810$. Again, the effect was fully developed in the fastest responses and did not change in slower ones (Figure 3B).

Priming effects as a function of occlusion

To further elucidate the relationship between priming effects and the number of occluders, we looked at the effects as a function of occlusion. Specifically, we measured post-hoc for every trial the respective number of visible edges (zero to six) and the amount of visible contours (pixels), averaged for the two triangles of the primes. To increase the statistical power, we defined a binary variable *visible edges* (VE) by averaging all trials with less than three visible edges (61.8% of trials) and all trials with three or more visible edges (38.2% of trials). For the variable *visible contours* (VC), we averaged all trials within each quartile of the full distribution of the visible contours (37.4, 51.3, 60.5, and 71.7 pixels, respectively). Because both variables are not independent and their operationalization is very different, we calculated separate ANOVAs for both factors, each including the additional factors of consistency (C) and prime-target SOA (S), but not the number of occluders.

Interestingly, we found that priming effects increased with the number of visible edges, $F_{C \times VE}(1, 7) = 13.16$, $p = 0.008$, as well as with the amount of visible contours, $F_{C \times VC}(3, 21) = 5.77$, $p = 0.005$. No other interactions including the factors were significant.

Summary

Together, the results from Experiment 1 suggest that self-splitting objects induce response priming effects in rapid visuomotor processing. With outline contours, these effects were independent of the number of occluders, and increased with SOA. With filled contours, the effects were decreasing with the number of occluders, and were not consistently increasing with SOA. At the same time, all priming effects were fully developed in the fastest responses and did not change in slower ones.

Experiment 2

In Experiment 2, we employed the same paradigm as in Experiment 1, except that we presented only filled contours and added a control condition without occluders. Importantly, we used an online response measure to directly check compliance with the rapid-chase criteria. Specifically, participants' response force (separately for the left and right index finger) was measured throughout the course of every experimental trial. This procedure has been used in a number of previous studies to investigate either the generation of motor responses in general (e.g., Jáskowski, van der Lubbe, Wauschkuhn, Wascher, & Verleger, 2000) or flanker effects specifically (Mattler, 2005).

Methods

Participants

Nine right-handed students from the University of Kaiserslautern, Germany (seven female, two male, ages 21-32), with normal or corrected vision participated in the experiment for payment of € 6 per hour. None of them had participated in Experiment 1. All of them provided written informed consent in accordance with the Declaration of Helsinki and were treated in accordance with the ethical guidelines of the American Psychological Association. They were debriefed after the final session.

Apparatus and stimuli

The apparatus and experimental surroundings were the same as in Experiment 1. Participants responded to the stimuli via pressing two (left, right) response buttons on a custom-made response force measurement system connected to a National Instruments USB-6008 data acquisition device (manufactured by Mag Design and Engineering, Redwood City, California, USA). The response buttons registered force electronically with a sampling frequency of 250 Hz. A force applied to the buttons resulted in a proportional voltage change with a resolution of about 0.02 cN (centi-Newtons). Response keys did not move when participants pressed them (isometric force).

The primes and targets were the filled contour stimuli of Experiment 1 (Figure 1C) with an additional condition in which prime triangles were presented without occluders. Stimulus arrangement was the same as in Experiment 1.

Procedure

The procedure was the same as in Experiment 1. The number of occluders in the primes varied randomly on

a trial-by-trial basis between none and three. Targets remained on screen for 1000 ms; again, the time interval from trial start to target onset was constant at 1000 ms (adding up to a total trial length of 2000 ms). Trial-by-trial feedback was provided by different tones, indicating correct, incorrect, or too weak (< 200 cN) responses. No summary feedback was provided. All stimulus combinations of consistency, prime-target SOA, and number of occluders occurred equiprobably and pseudo-randomly in a completely crossed repeated-measures design. Each participant performed four sessions with one practice block of 32 trials followed by 26 blocks of 32 trials, accumulating to a total of 3,328 trials per participant.

Data treatment and statistical methods

Practice blocks were not analyzed. Trials were excluded from analysis if neither of the buttons was pressed with more than 200 cN throughout the respective trial (0.53 % of trials). We did not define or exclude errors because in response priming, errors in inconsistent trials are predominantly driven by prime information (e.g., F. Schmidt & Schmidt, 2010; T. Schmidt et al., 2006). Indeed, we were explicitly interested in contrasting the forces that were simultaneously exerted to both response buttons, without excluding trials on grounds of a priori and arbitrarily set error thresholds.

We calculated the difference between the force exerted on the correct target button and that exerted on the incorrect target button throughout the time course of each trial. Consequently, the values of the resulting *force trajectories* were positive when participants exerted relatively more force on the correct than on the incorrect target button (and vice versa for negative values). The trajectories were averaged within the experimental conditions defined by combinations of the factors consistency, prime-target SOA, and number of occluders. For temporal priming effects, we compared the times when the force trajectories in consistent and inconsistent trials crossed two spatial criteria (onset criterion, completion criterion).

To calculate priming effects in response force, we defined a *force priming function* by subtracting force trajectories in consistent trials from those in inconsistent trials (negative values indicating how much stronger the incorrect target button was pressed in inconsistent trials compared to consistent trials at corresponding points in time). We analyzed these force priming effects by calculating their onset, peak amplitude, and time of their peak amplitude. Equivalently to spatial priming functions obtained from pointing responses, the force priming functions can be assessed with respect to their compliance with the rapid-chase criteria (e.g., F. Schmidt & Schmidt, 2009, 2010; T. Schmidt, 2014; T. Schmidt et al., 2006).

The parameters of the force trajectories and force priming functions were extracted by jackknifing methods (Ulrich & Miller, 2001). Force trajectories of the *n* participants were averaged across each subsample of (*n*-1) participants, excluding a different participant from each subsample. Onset and completion times as well as peak amplitude and time of peak amplitude were estimated from each subsample and then averaged. This procedure allows for estimates that are much more reliable than those from single participants, without altering the average trajectories (Ulrich & Miller, 2001).

We performed repeated-measures analyses of variance (ANOVAs) (separately for the different numbers of occluders) that were fully factorial with factors of consistency (*C*), prime-target SOA (*S*), and number of occluders (*O*). To account for the jackknifing of the data, *F* tests were corrected to estimate variation among participants rather than among subsamples (Ulrich & Miller, 2001).

Results and discussion

Force trajectories: General

In consistent trials, participants typically exerted stronger force on the correct than on the incorrect target button. Force on the incorrect button was negligible. However, in inconsistent trials, participants typically exerted stronger force on the *incorrect* than on the correct target button at the beginning of the trial and only later exerted stronger force on the correct target button. This initial force in the direction of the misleading prime was earlier and stronger with increasing SOA and strongly decreased with an increasing number of occluders. In fact, it was most pronounced in the absence of occluders, whereas responses with occluders in inconsistent trials were merely delayed by the inconsistent prime.

For statistical analysis, we defined the points in time where the force trajectories exceed criteria of 200 cN (onset criterion) and 600 cN (completion criterion), respectively. Two criteria are necessary because the magnitude of temporal priming effects varies over the time course of the response (e.g., T. Schmidt, 2002; F. Schmidt & Schmidt, 2009). An ANOVA revealed a priming effect in both onset and completion times, $F_C(1, 8) = 55.02$, $p < 0.001$; $F_C(1, 8) = 26.17$, $p = 0.001$, that decreased with an increasing number of occluders, $F_{C \times O}(3, 24) = 43.33$, $p < 0.001$; $F_{C \times O}(3, 24) = 13.16$, $p < 0.001$. To analyze these results in more detail, we performed separate ANOVAs for the different numbers of occluders with factors of consistency (*C*) and prime-target SOA (*S*).
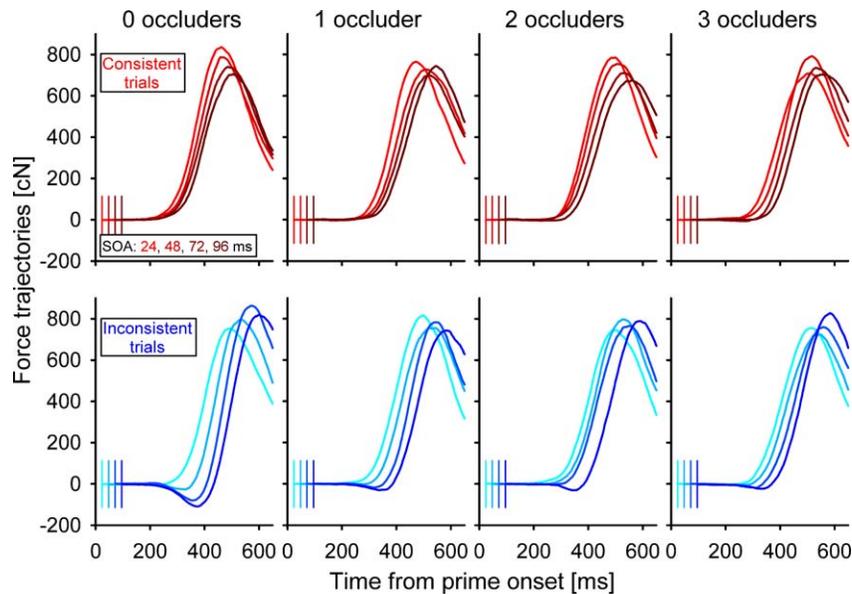
Figure 4. Force trajectories in Experiment 2 for the different number of occluders in consistent (upper panels, red) and inconsistent trials (lower panels, blue). Trajectories are defined by the difference between the force exerted on the correct target button and that exerted on the incorrect target button. The trajectories of the different SOAs are depicted by different shades of color. The time axis is locked to prime onset; the times of target onset for the different SOAs are denoted by the vertical lines.

Force trajectories: No occluders

The results with occluders absent are depicted in the leftmost panels in Figure 4. Onset and completion criteria were crossed earlier in consistent compared to inconsistent trials, $F_C(1, 8) = 69.02$, $p < 0.001$; $F_C(1, 8) = 71.30$, $p < 0.001$, and the priming effect in onset times increased with SOA, $F_{C \times S}(3, 24) = 28.96$, $p < 0.001$.

Force trajectories: One, two, and three occluders

The results with occluders present are depicted in the right panels of Figure 4. Onset and completion criteria were crossed earlier in consistent compared to inconsistent trials, one occluder: $F_C(1, 8) = 24.72$, $p = 0.001$; $F_C(1, 8) = 6.25$, $p = 0.037$; two occluders: $F_C(1, 8) = 28.54$, $p = 0.001$; three occluders: $F_C(1, 8) = 19.01$, $p = 0.002$. However, the priming effect in onset times increased with SOA only with one occluder, $F_{C \times S}(3, 24) = 5.10$, $p = 0.007$, and two occluders, $F_{C \times S}(3, 24) = 3.58$, $p = 0.029$, but not with three occluders.

Force priming functions: General

Typically, the force priming functions started out by developing in the negative direction, thereby demonstrating the initial influence of the prime. For statistical analysis, we defined the onset of the force priming effect when it first fell below -50 cN, that is, when the difference between the force exerted on the correct and incorrect target in inconsistent trials exceeded that in consistent trials by 50 cN. Importantly, this criterion

was crossed later with an increasing number of occluders, $F_O(3, 24) = 15.35$, $p < 0.001$. Also, the peak amplitude of the force priming functions was smaller (i.e., less negative) with an increasing number of occluders, $F_O(3, 24) = 81.04$, $p < 0.001$, and by trend occurred later, $F_O(3, 24) = 2.51$, $p = 0.083$. To analyze these results in more detail, we performed separate ANOVAs for the different numbers of occluders with the factor of prime-target SOA (S). Generally, all peak amplitudes were significantly different from zero, all $F_{Intercept}(1, 8) > 20.54$, all $p < 0.002$, thus force priming effects occurred with any number of occluders.

Force priming functions: No occluders

The results are depicted in the leftmost panel of Figure 5. With occluders absent, the time course of the force priming functions conformed to a pattern predicted by the rapid-chase theory. Priming functions were strictly time-locked to prime onset, in line with the notion that the force priming effect was actually triggered by the prime (initiation criterion). Crucially, the early time course of the force priming functions was invariant for the different SOAs: All curves initially followed the same time course and branched off only later one by one in the order of increasing SOAs (independence criterion). Once the force priming functions started to depart from the common time course, they strongly depended on SOA (takeover criterion). This pattern of results exactly matches that observed in response priming with pointing responses
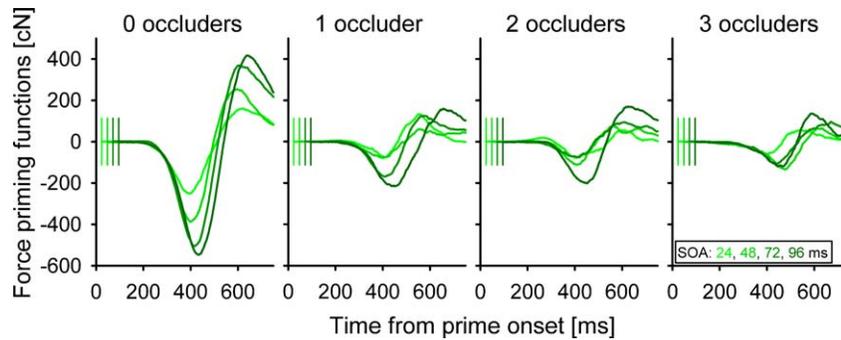
Figure 5. Force priming functions in Experiment 2 for the different number of occluders. Trajectories are defined by the difference between force trajectories in consistent trials and those in inconsistent trials (negative values indicating how much stronger the incorrect target button was pressed in inconsistent trials compared to consistent trials). It is a strong prediction of rapid-chase theory that in rapid-chase systems the early time course of the priming functions is invariant for the different SOAs. The trajectories of the different SOAs are depicted by different shades of color. The times of target onset for the different SOAs are denoted by the vertical lines.

(F. Schmidt & Schmidt, 2009, 2010; T. Schmidt et al., 2006).

The onset of the force priming effect with no occluders was at 275 ms and independent of SOA, $F_S(3, 24) = 0.07$, $p = 0.978$. At the same time, the peak amplitude was reached later and became more negative with increasing SOA, $F_S(3, 24) = 17.41$, $p < 0.001$; $F_S(3, 24) = 5.17$, $p = 0.007$.

Force priming functions: One, two, and three occluders

The results are depicted in the right panels of Figure 5. With occluders present, the time course of the force priming functions did not conform to a pattern predicted by rapid-chase theory. While there is evidence that one occluder still allows for rapid-chase processing (invariant initial time-course across different SOAs), responses were not strictly time-locked to prime onset. Priming effects in general were smaller and increased with SOA only with one and two occluders.

The onset of the force priming effects with an increasing number of occluders was at 340, 349, and 372 ms, respectively, and was independent of SOA in each of these cases, all $F_S(3, 24) < 0.93$, all $p > 0.440$. The peak amplitude increased with SOA only with one and two occluders, $F_S(3, 24) = 9.71$, $p < 0.001$; $F_S(3, 24) = 6.66$, $p = 0.002$. The time of the peak amplitude was independent of SOA for all occluder conditions, all $F_S(3, 24) < 1.81$, all $p > 0.173$.

Summary

The results from Experiment 2 extended our findings from Experiment 1. Self-splitting objects induced response priming effects in force responses within rapid visuomotor processing. The magnitude of these effects decreased with an increasing number of occluders while the typical boosting effect of SOA on response priming effects deteriorated. While priming effects strictly conformed to the rapid-chase criteria when occluders were absent, they increasingly failed to meet these requirements when the number of occluders increased.

General discussion

We set out to determine the processing dynamics and time course of Good Gestalt to draw conclusions about the type of neuronal processing underlying it (feedforward versus feedback). Also, we wanted to investigate whether the amount of occlusion would modulate this processing. Because the principle of Good Gestalt plays a major role in the perception of self-splitting objects, we tested the influence of shapes that were part of self-splitting objects (Petter, 1956) on rapid visuomotor responses. The *primed flanker task* (F. Schmidt & Schmidt, 2013, 2014) provides information not only about the absolute speed of processing but also about the type of processing (based on predictions by rapid-chase theory; T. Schmidt et al., 2006).

Generally, we wanted to know whether the primes led to response priming effects in response times, error rates, and force responses, indicating fast processing of self-splitting objects. Specifically, we were interested in whether these effects (a) would be different for outline and filled contours, (b) would depend on the number of occluders, and (c) would meet the rapid-chase criteria indicating feedforward processing.

Indeed, we obtained priming effects in response times as well as error rates for outline and filled contours that increased with SOA (exceptions discussed below), corresponding to earlier findings in response

priming experiments (cf. T. Schmidt, Haberkamp, Veltkamp, et al., 2011). These effects were also evident in force responses and demonstrate the capability of the visual system to extract and process the orientation of a triangle from very briefly presented (24 ms) overlapping contours even when merged into one single shape. Notably, the priming effects in response times were fully present in the fastest responses and did not increase any further in slower responses. Together, these findings suggest that self-splitting objects were split into their components by the visual system rapidly enough to not only influence visuomotor processing of the targets, but also to influence the fastest responses in particular.

When analyzing and comparing the results for the outline contours with those for the filled contours, we can draw several conclusions. On the level of overall response times and error rates, results were similar for the two stimulus classes. Differences emerged mainly with respect to the influence of the number of occluders and with respect to the indicators of feedforward processing. The specific pattern of results with filled contours was also replicated and supported by response force data. We will discuss the implications in detail in the following sections.

The role of the number of occluders

With respect to overall response times, the number of occluders had a similar effect for outline and filled contours. More occluders slowed down response times, most probably reflecting the higher complexity of the respective primes. Specifically, with more occluders the primes contained more potentially task-irrelevant information (i.e., more edges and contours). This information was automatically analyzed by the visual system which increased the overall processing time.

However, with respect to priming effects, the number of occluders had different effects depending on stimulus class. With outline contours, occluders played no role for the magnitude of the priming effects, at least in response times. Even with three occluders (i.e., a total of four overlapping contours) the visual system was still able to extract the task-relevant triangle from the briefly presented tangle of lines. For error rates, however, priming effects were largest with one occluder, and smaller in trials with two or three occluders. With filled contours, occluders had a greater role in shaping the priming effects. Most importantly, priming effects in response times and force responses decreased with an increasing number of occluders. Also, even though the priming effects were still present with two and even three occluders, they no longer increased with increasing SOA. This

failure to increase with SOA is important because it represents a violation of a prediction from rapid-chase theory. With regard to the priming effects in error rates, the result pattern was the same for filled contours as for outline contours.

Indicators of feedforward processing

When analyzing the response time functions, we observed priming effects for outline and filled contours in all phases of the participants' responses. The effects were fully present in the earliest responses and did not decrease in slower ones. According to rapid-chase theory, this pattern is consistent with a feedforward system where prime and target signals traverse the visuomotor system in strict sequence, without mixing or overlapping (T. Schmidt et al., 2006; Vath & Schmidt, 2007).

Results for outline contour primes show that the visuomotor system is able to process those features that are relevant for its response, namely, the non-occluded edges and contours of the triangles in the two prime stimuli. Moreover, this processing seems to occur in a feedforward fashion. A similar pattern of results for filled contour primes (i.e., self-splitting objects) would imply that the prime configurations can be broken down into their components without the necessity of extensive recurrent processing. However, priming effects showed the typical pattern of an increase with SOA only when the number of occluders was limited to one. The results for two and three occluders were somewhat mixed: The shape of the response time functions argues in favor of feedforward processing while the lack of the typical SOA effect calls feedforward processing into question (cf. F. Schmidt & Schmidt, 2014). We conclude that even though the processing of self-splitting objects is implemented early on in visuomotor processing, the amount of occlusion determines whether it occurs in a feedforward fashion or whether recurrent processing is necessary. This conclusion is strongly supported by the time course of the force priming effects. Rapid-chase criteria are clearly met with occluders absent, but increasingly less so when more occluders are present.

With regard to our stimulus set, only self-splitting objects comprised of two objects were processed in a feedforward manner, as indicated by the increasing priming effects with increasing SOA, the fully present effects in earliest visuomotor responses, and the early invariant time course of force priming effects. This result suggests that the visual system is able to complete two tasks within this early phase of processing of self-splitting objects with one occluder. First, a sufficient number of key features are extracted to identify the task-relevant object, that is,

all relevant angles and edges to distinguish between an upward and a downward pointing triangle.[2] This first task of extraction is illustrated by our post-hoc analyses in Experiment 1, which demonstrates that the response time priming effects increased with the number of visible edges and the amount of visible contours. Second, these features are processed in a feedforward manner without extensive recurrent processing, and activate a rapid motor response.

Our results might suggest that the processing of self-splitting objects with one occluder is more similar to the processing of illusory contours (modal completion) than to that of visual completion with occluded objects (amodal completion). Processing of illusory contours was shown to be generated by relatively local integration of signals implemented by feedforward signals (e.g., Heitger, von der Heydt, Peterhans, Rosenthaler, & Kübler, 1998; cf. Seydell-Greenwald & Schmidt, 2012), while visual completion is most probably implemented by feedback activation from higher levels (Sugihara, Qiu, & von der Heydt, 2011; Zhang & von der Heydt, 2010). Note that this attribution of modal and amodal completion to feedforward and feedback activation, respectively, is not without controversy. Kogo and Wagemans (2013) argue that both processes rely on the computation of "border-ownership" (BOWN), that is, on the decision which borderline is "owned" by which shape. BOWN is not a physical property of the image but a result of its global configuration and its interpretation. The most important aspect of this interpretation is related to the depth-ordering of shapes. For example, in amodal completion, the borderline between two shapes would be owned by the shape that is perceived as being on top of (i.e., is occluding) the other shape. It is conceivable that the neurons that are sensitive to BOWN (Zhou, Friedman, & von der Heydt, 2000) are also activated by the illusory contours in modal completion (Kogo & Wagemans, 2013). This premise would suggest that the perception of illusory contours follows from the activation of BOWN-sensitive neurons as a result of global interactions in the BOWN computation (i.e., follows from feedback signals).

Although Kogo and Wagemans (2013) seek to explain modal and amodal completion within a single framework, they do not explicitly discuss quasi-modal completion (i.e., self-splitting figures). In our results, self-splitting objects are not processed uniformly but strongly depending on the amount of occlusion. So what is the difference between processing of self-splitting objects with different amounts of occlusion? How is the rapid feedforward processing of self-splitting objects with one occluder implemented in the visuomotor system?

Implementation of feedforward processing

The visual system has stored a vast number of Gestalt templates as a result of previous visual experience (Wagemans et al., 2012b). In terms of neural architecture, these templates correspond to feature detectors that are tuned to specific constellations of lower-level features including a large number of simple but also some complex shapes (e.g., Barlow, 1972; Tanaka, Saito, Fukada, & Moriya, 1991; cf. *base groupings*; Roelfsema, 2006). The templates are constantly matched with the incoming visual information. This process of template matching or searching for a set of key features to recognize an occluded object or shape (i.e., to establish *analogies*; Bar, 2007) can be described in terms of computational modeling (e.g., Ullman, 1992; Ying & Castañon, 2002) and may also apply to self-splitting objects. In the current experiments, the activation of two templates (i.e., an upward and a downward pointing triangle) is sufficient to solve the task. But how does this template matching result in response priming effects?

Specifically with respect to response priming, participants generally establish *action triggers* (Kiesel, Kunde, & Hoffman, 2007) depending on task instructions (e.g., "respond to the upward oriented triangle") that tie specific stimuli or features to specific responses (*direct parameter specification;* Neumann, 1990). As a result, the template of a task-relevant stimulus is directly linked to the execution of the visuomotor task. If one of the stored templates is task-relevant and a sufficient number of its key features matches the visual input, that input is used immediately to guide visuomotor processing (i.e., within the first feedforward processing phase) even if it is not task-relevant (primes). The amount of occlusion of the prime triangles matters because it decreases the number of visible key features. As a consequence, the matching process becomes more difficult and requires more extensive neuronal activation (i.e., feedback).

This also explains the principal difference between our results for outline and filled contours in Experiment 1. The amount of occlusion of the prime triangles is much lower when the contours are defined by outlines. As a consequence, most of the key features are uncompromised, and processing can occur in accordance with a feedforward account.

Note that the general explanation of our results is in accordance with a preselection of the triangles by attention. This top-down attention would bias the competition between the different shapes in favor of the triangles (*biased competition*, Desimone & Duncan, 1995) or in favor of the triangles' features (*feature similarity gain model*, Treue & Martinez-Trujillo, 1999). On the neuronal level, this competition is reflected in an

increase in neuronal activation for a specific shape (e.g., demonstrated in monkey V2 by Qiu, Sugihara, & von der Heydt, 2007). On the behavioral level, top-down attention is reflected in increased response priming effects for shapes with a specific feature (cf. F. Schmidt & Schmidt, 2010).

Implications for Good Gestalt

But what do our results tell us about the principle of Good Gestalt? From our findings, we conclude that the implementation of Good Gestalt is not based on feedforward processing. The criteria of rapid-chase theory are met only for self-splitting objects with at most one occluder, a case in which the visuomotor response may still be based on activation of groups of specific feature detectors. However, the Good Gestalt principle is more general and implies that all self-splitting objects split into shapes that are as simple, regular, and well-structured as possible. Therefore, it should also apply to primes with more than one occluder. As the pattern of priming effects shows, these primes indeed are split into their components within a phase of rapid visuomotor processing, but this occurs more slowly compared to primes with only one occluder, and turns out not to be consistent with a feedforward account once formal criteria are applied (T. Schmidt, 2014). Thus, with two or three occluders, recurrent processing seems necessary to split the tangled shapes into their components. This is the case even though the spatial positions of the primes were not changing and the task-relevant shapes were limited to an upward and a downward pointing triangle. We conclude that even though the implementation of the principle of Good Gestalt is relatively fast, it is still based on recurrent processing.

Keywords: self-splitting objects, occlusion, completion, feedforward processing, priming

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Footnotes

[1]Note that this originally quite vague definition was later subject to strict formalizations (cf. the *minimum principle*; e.g., Attneave, 1954; Hochberg & McAlister, 1953; the *likelihood principle*, e.g., Pomerantz & Kubovy, 1986; or the *simplicity principle*, e.g., Leeuwenberg, 1969; for a review and discussion see Wagemans et al., 2012b).

[2]This extraction is easier the more features are visible, a fact that was described earlier in terms of the *support ratio*: the ratio of physically specified (visible) length to total edge length in occluded shapes. An increasing support ratio increases the perceived connectedness of two contour segments separated by an occluder as well as the perceived strength of an illusory contour (e.g., Shipley & Kellman, 1992).

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