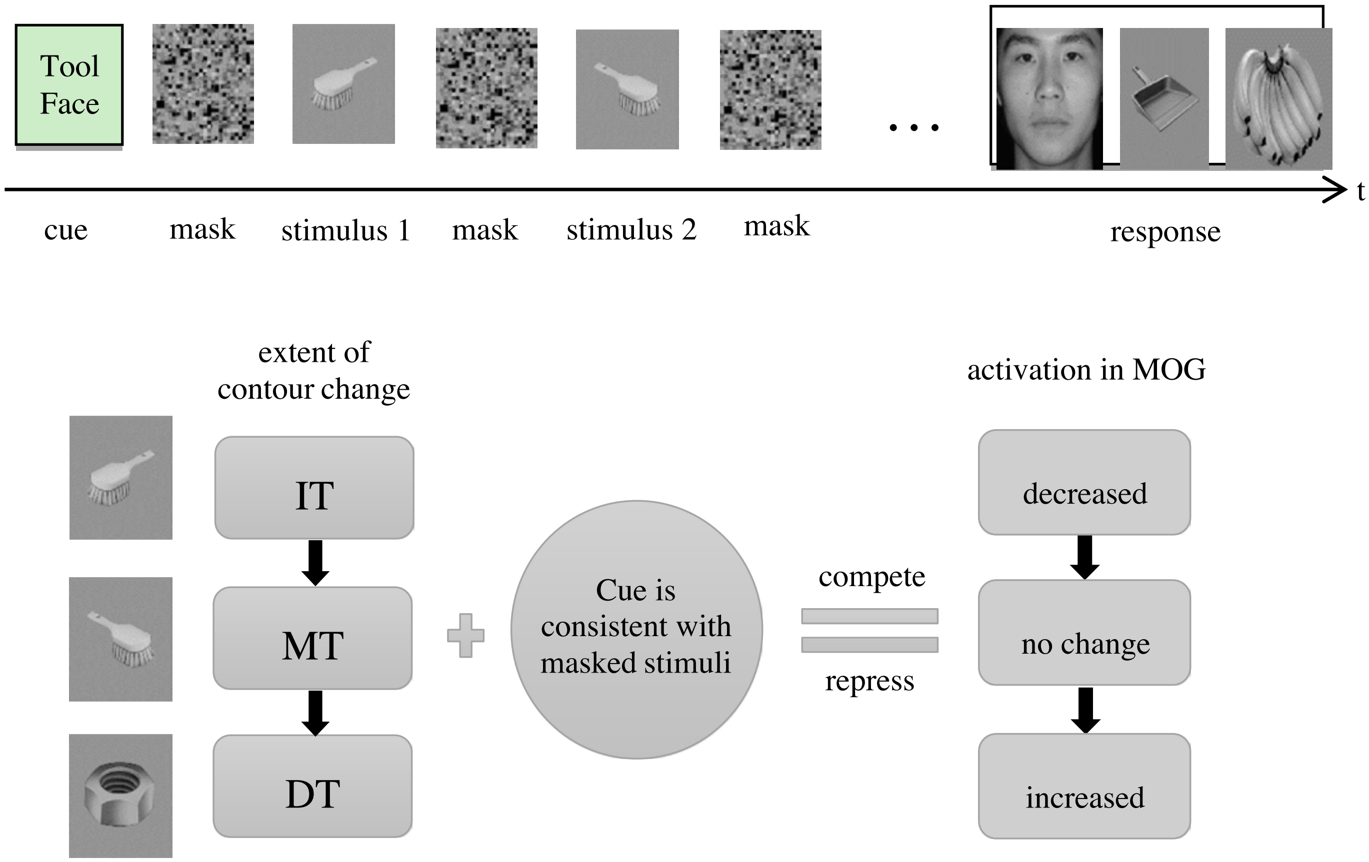

IT = masked invariant tool picture; MT = masked variant mirror-image tool picture; DT = masked different tool picture.

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Category-selective attention interacts with partial awareness processes in a continuous manner: An fMRI study

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Abstract: Recently, our team found that category-selective attention could modulate tool processing at the partial awareness level and unconscious face processing in the middle occipital gyrus (MOG). However, the modulation effects in MOG were in opposite directions across the masked tool and masked face conditions in that study: MOG activation decreased in the masked faces condition but increased in the masked tools condition under the consistent compared with the inconsistent cue-selective-attentional modulation. In the present study, in order to confirm that the opposite effects were due to the changed contours of the tools, using the same tool pictures and fMRI technique, we devised another two conditions: variant mirror tool picture condition and invariant tool picture condition. The results showed that, during the variant mirror tool picture condition, activation in the MOG decreased under tool-selective attention compared with face-selective attention. Interestingly, however, during the invariant tool picture condition, activation in the MOG revealed neither positive nor negative changes. Combined with the result of increased MOG activity in the changed different tool condition, the three different effects demonstrated not only that the unconscious component of partial awareness processing (no knowledge of the identity of the tool) could be modulated by the category-selective attention in the earlier visual cortex but also that the modulation effect could further interact with the conscious component of partial awareness processing (consciousness of the changing contour of the tool) in a continuous manner.


Shen Tu

ABOUT THE AUTHOR

Shen Tu is a lecturer of Psychology at China West Normal University. He earned PhD in Developmental and Educational Psychology from Southwest University in China. The main present focus of his research and his associates is on the relationship between conscious and unconscious processes, which has two possible aspects: interactions within conscious/unconscious processes, and between conscious and unconscious processes. Specifically, Shen Tu and the coauthors focus on the conscious modulations on unconscious processes and whether and how different unconscious processes interact with each other. The present paper is part of a serial of studies about the conscious modulations on unconscious processes.

PUBLIC INTEREST STATEMENT

We found several results of interest. First, our perceptual system can process stimuli without our awareness. Second, our conscious expectation can influence the unconscious perception and processing of a stimulus. Thus, the division between consciousness and unconsciousness is not clear. Third, consciousness is not a dichotomous experience, but a graded one. People can be partially conscious of a stimulus. In other words, we can be aware of the existence or some features of a stimulus (conscious component), but not of the identity (unconscious component) of the stimulus. Lastly and most importantly, the conscious and unconscious processing could interact in a complex way. In our study, top-down influences on unconscious component processing of partially conscious stimuli can interact with the conscious component processing of the partially conscious stimuli in a continuous manner.

Subjects: Behavioral Neuroscience; Cognitive Neuroscience; Cognitive Psychology; Multidisciplinary Psychology; Neuropsychology; Psychological Science

Keywords: top-down; category-selective attention; unconscious processes; partial awareness; continuous manner; fMRI

1. Introduction

There are two ways by which consciousness states can interact with each other (Tu & Zhao, 2014): interactive influences within conscious or unconscious processes, and influences between conscious and unconscious processes. The former includes: (1) the interactive influences between conscious processes, which mainly reflect the role of attention on conscious processing (Carrasco, 2011; Cohen, Cavanagh, Chun, & Nakayama, 2012); (2) the interactions between unconscious processes, e.g. different unconscious processes influencing each other, leading to higher level unconscious processes (Tu, Martens, et al., 2013; Tu & Zhao, 2014). Regarding the latter, unconscious priming studies have revealed that unconscious information can affect subsequent conscious processing of information (Faivre & Kouider, 2011; Li, Paller, & Zinbarg, 2008). Likewise, conscious processes can also modulate subsequent unconscious processes (Kiefer & Martens, 2010; Martens & Kiefer, 2009; Marzouki, Grainger, & Theeuwes, 2007). Moreover, although consciousness can be dichotomous under some conditions, it can also be graded under other conditions (Windey, Vermeiren, Atas, & Cleeremans, 2014). Therefore, there can be an intermediate or partial state of consciousness between a completely conscious and a completely unconscious state (Kouider, de Gardelle, Sackur, & Dupoux, 2010). In a completely conscious or aware state, the observer is confident that he or she fully perceives the presence and understands the identity of a target stimulus. In a completely unaware state, the observer does not sense the presence of a stimulus or any fragment or component of the contents of the stimulus, let alone the identity of the stimulus. A partial awareness state is one in which an observer senses some fragments or features of a stimulus without being able to determine its identity due to either the degraded nature of the stimulus caused by masking or a brief display period or divided attention (Kouider et al., 2010). How conscious top-down attention influences the information in partial awareness is unclear. Specifically, how conscious top-down processes interact with the unconscious level of representation in partial awareness is unknown.

In a recent study, Tu, Qiu, Martens, and Zhang (2013) presented a category cue word (e.g. face or tool) and followed it with a rapid serial presentation (with a stimulus duration of 16 ms) of either masked faces or masked tools. They found that participants were completely unaware of the presented faces but partially aware of the tools. That is, participants reported that they could not see anything of the rapidly presented faces, but that they could see some changing contours of the tools even though they could not identify what the objects were. Interestingly, Tu, Qiu, et al. (2013) found that category-selective attention or an expectation of a category of stimuli generated by the cue word could influence both subsequent unconscious face processing and partially conscious tool processing. Since it is an expectation, it is a form of top-down attention (Chun, Golomb, & Turk-Browne, 2011). In other words, the selective conscious, top-down attention invoked by the category cue can modulate both the completely unconscious and partially conscious stimulus processing that follows the cue word. The face contours in the presentation in Tu, Qiu, et al. (2013) experiment remained basically the same over the five rapid presentations whereas the tool contours changed from one masked presentation to the next. Tu, Qiu, et al. (2013) compared the middle occipital gyrus (MOG) activation levels across the face-cue-word/masked-face-display (FF), face-cue-word/masked-tool-display (FT, also called FDT because the five masked tools are different tools which have different contours), tool-cue-word/masked-tool-display (TT, also called TDT), and tool-cue-word/masked-face-display (TF) conditions. According to the predictive coding theory (Rao & Ballard, 1999), when the information in the cue is consistent with the visual information following the cue, activity in the early visual cortex will decrease compared with when the following information is inconsistent with the cue. We evaluated the MOG activation in these two conditions by comparing it with a baseline condition where either the face-cue-word was followed by a blank display (FB) or a tool-cue-word followed by a blank display (TB). Tu, Qiu, et al. (2013) found that for the masked face processing, the modulation activation in the MOG decreased after the face selective attention cue compared with the tool selective attention cue, i.e. (FF − TF) < (FB − TB), which was consistent with the predictive coding theory (see Figure 1(A)). In contrast, for the masked different-tool processing, the modulation activation in the MOG increased under the tool selective attention cue compared with the face selective attention cue, i.e. (TDT − FDT) > (FB − TB), which was the opposite of what the predictive coding theory predicts (see Figure 1(A)). To explain these results, the authors proposed an "excessive activation" hypothesis. According to that idea, although participants could not identify the masked presented tools, they were aware of the changing contours of the tools or partially aware of the presence of tools. When the unconscious "meaning" of the masked presented tools was consistent with the cue word, the incongruity caused by the changed contours could generate excessive activation in the MOG (Tu, Qiu, et al., 2013). The authors argued that this was an instance of selective conscious attentional modulation on the unconscious meaning of the masked targets interacting with a partially conscious process.

As noted above, in Tu, Qiu, et al.'s (2013) study, face and tool target conditions involved different conscious states, with face processing being completely unconscious and tool processing being partially conscious. In that study, although the tool targets in the serial display had changing contours (there were five different tool pictures with different contours in a trial) which was similar to the repetition paradigm (Valyear, Gallivan, McLean, & Culham, 2012) and block design (Vingerhoets, 2008) employed in previous research, the face targets did not (the five faces basically had the same contours). Therefore, different states of consciousness (partially conscious vs. completely unconscious) and the changing vs. constant contours of the masked targets might have both played a role in causing the opposite patterns of results for the face and the tool processing conditions in the Tu, Qiu, et al.'s study (2013). In the present fMRI study, in order to determine whether only the changed contours of the tools could explain the opposite effects for the face and the tool cue conditions, we devised two additional conditions presented at the partial awareness level: a variant mirror-image tool picture condition (MT) and an invariant tool picture condition (IT).

Based on the predictive coding theory (Rao & Ballard, 1999) and the "excessive activation" hypothesis (Tu, Qiu, et al., 2013), we expected that the modulation activation in the MOG in the masked invariant tool picture condition would decrease after the tool selective attention cue compared with the face selective attention cue. Note that neither of the above conditions involved a contour change in the serial masked display and therefore both were expected to produce results similar to those in the completely unconscious face processing condition in Tu, Qiu, et al.'s (2013) experiment. However, for the masked variant mirror-image tool picture condition, the excessive activation hypothesis predicts that the modulation activation in the MOG should increase after a tool selective attention cue compared with a face selective attention cue, which would be similar to the tool processing at a partial awareness level in Tu, Qiu, et al.'s (2013) experiment.

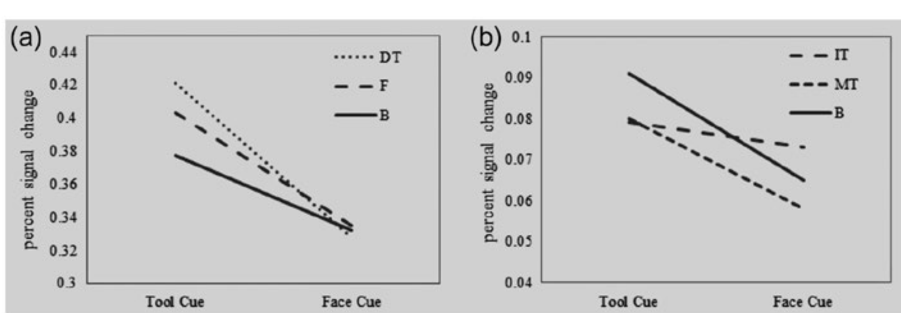


Figure 1. The percent signal change for each condition. (A) Data in Tu, Qiu, et al. (2013): (FF − TF) < (FB − TB), (TDT − FDT) > (FB − TB). (B) Data in the present study: (TIT − FIT) < (FB − TB), (TMT − FMT) = (FB − TB)

Notes: IT is the masked invariant tool picture; MT is the masked variant mirror-image tool picture; DT is the masked variant different tool picture; F is the masked face picture; B is the masked blank screen.

Some previous studies have suggested that top-down attentional modulations on input visual information take place in the visual cortex (Bahrami, Lavie, & Rees, 2007; Rauss, Schwartz, & Pourtois, 2011). Also, since the design in the present study was the same as in the Tu, Qiu, et al.'s (2013) study in which the top-down modulation was reflected in the MOG activation levels, we considered it reasonable for us to use the MOG activities in the present study as an index of a top-down modulation effect. There is a need to mention an unexpected result of the present study here: the category-selective modulation effect could interact with the conscious component of the partial awareness processing (i.e. subjects' awareness of the changing contour of the tool) in a continuous manner. As far as we know, this is the first time that the continuous nature of the interaction between top-down modulation and partial awareness processing was revealed.

2. Materials and methods

2.1. Participants

A total of 20 adults (9 women and 11 men aged between 19 and 26 years; mean age 21.3 years) participated in this experiment voluntarily. All participants were right-handed and had normal or corrected-to-normal vision. No history of neurological or psychiatric disorders was reported. All participants gave written informed consent after which the nature of the study was explained to them. This study has been approved by the IRB at Southwest University.

2.2. Stimuli

Twenty tool pictures and 20 pictures of other categories (e.g. faces, animals, fruits) were selected from the Internet as stimuli. All the pictures were grayscale images. In addition, all tool pictures were bilaterally asymmetrical to produce their mirror images. All mirror-image tool pictures were made from the original 20 pictures resulting in 40 tool pictures in total. In the experiment, the pictures were displayed centrally on a uniform gray background and each picture subtended approximately 4.3 (height) × 3.8 (width) degrees of visual angles.

2.3. Procedure

E-prime 2.0 Software (Psychology Software Tools, Inc. http://www.pstnet.com) was used for presenting stimuli and recording behavioral data. There were six experimental conditions: face cue with masked invariant tool picture (FIT), face cue with masked variant mirror-image tool picture (FMT), face cue with masked blank screen (FB), tool cue with masked invariant tool picture (TIT), tool cue with masked variant mirror-image tool picture (TMT), and tool cue with masked blank screen (TB) in which no stimulus was presented. To avoid differences in low-level features, masked tools were counterbalanced between the FIT and TIT conditions, as were those between FMT and TMT and MT and IT conditions (Figure 2). Therefore, category-selective attention modulations on tool processing at the partial awareness level could not be attributed to low-level stimulus differences.

In the experiment, participants were asked to decide at the end of a trial whether a supraliminally presented picture matched the category given by a word cue at the beginning of a trial to make them attend to and retain the cue word during the trial. Between the cue word and the supraliminal picture, five masked tool pictures or five blank screens were presented. The stimulus sequence in a trial, which was similar to that in the study of Tu, Qiu, et al. (2013), was as follows (Figure 3): a cue word ("tool" or "face") was first displayed for 500 ms followed by a scrambled picture which served as a forward mask for 383 ms. Then a target of a tool picture or a blank screen appeared for 16 ms, which was followed by a backward mask for 384 ms. As in Tu, Qiu, et al. (2013), the masked targets (a tool or a blank screen) and the backward masks were repeated five times. However, in this experiment, there were two tool presentation versions. In the invariant version, the same tool picture was repeated five times within a trial. In the mirror-image version, a tool picture and its mirror image appeared alternately and the sequence of them was counterbalanced. The last mask was displayed for 400 ms, followed by a supraliminally displayed picture (either a tool, a face, a fruit or an animal) for 1,600 ms. Participants were asked to decide whether this picture matched the category of the word cue as quickly and accurately as possible by pressing a response button on a button box. The

Figure 2. Examples of masked stimuli.

Notes: Left: invariant tool pictures. Right: variant mirror-image tool pictures. The pictures were counterbalanced between IT and MT conditions.

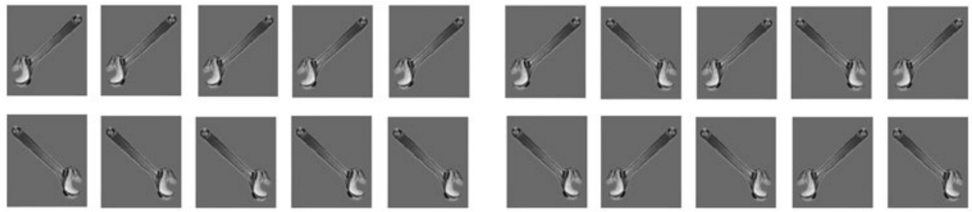
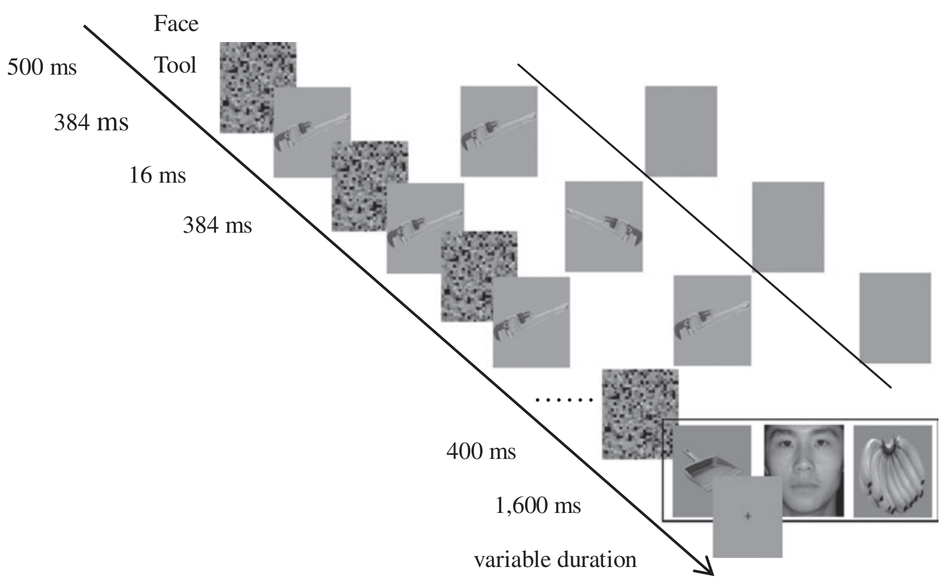


Figure 3. Schematic illustration of the task.

Notes: Participants were required to determine whether the last unmasked picture matched the word cue presented at the beginning of the sequence, and told that the stimuli between the word cue and supraliminal picture were distractors. Left: invariant tool pictures condition. Middle: variant mirror-image tool pictures condition. Right: blank condition.



participants were also informed that the masked stimuli were distractors. Between trials, a central fixation cross was presented for a jittered inter-trial interval of 2–6 s. Each condition contained 40 trials resulting in 240 trials in total separated into two runs. The different conditions were displayed pseudorandomly. The response to response-key assignment was counterbalanced across participants. There were 70% consistent (the supraliminal picture matched the category of the word cue) and 30% inconsistent (the supraliminal picture did not match the category of the word cue) trials.

After fMRI scanning, an objective forced-choice task and a subjective report were conducted to evaluate the participants' ability to recognize the masked tool pictures. The objective task preceded the subjective task. Before the objective forced-choice task began, participants were informed that a masked tool picture was repeatedly presented in each trial and that only the accuracy of their response was important. During this objective measure, participants were asked to make a forced-choice discrimination while still lying in the scanner. The procedure was similar to that used during fMRI scanning, except that the IT and MT conditions were tested in two separate blocks with 20 trials in each block. In each trial, after the presentation of the last mask, two tool names with one denoting the same tool as the masked tool picture presented before and the other naming a different tool were displayed on the left and right of the fixation point. Words but not pictures were used to avoid possible contour confusion (Tu, Qiu, et al., 2013). Participants were asked to judge which word matched the masked tool target. The two words remained on the screen until the participant made a response. For the subjective report, the participants were asked to tell whether they could sense the changes of contours and orientations of the masked tool pictures and whether they could tell what the masked tool pictures were for IT and MT blocks, respectively. The combination of the objective measure and subjective report was used to reveal whether the participants were partially aware of the masked pictures but unable to identify them.

2.4. fMRI data acquisition

Imaging data were acquired with a 3-T Siemens Trio Scanner (Siemens Medical Systems, Erlangen, Germany) using a 12-channel birdcage headcoil. Two functional scans were acquired using an echo planar imaging (EPI) sequence (TR = 2,000 ms, TE = 30 ms, flip angle: 90°; field of view: 220 × 220 mm^2; matrix size: 64 × 64). Each functional volume consisted of 32 axial slices of 3 mm thickness with a 1 mm gap between slices. Each scan lasted approximately 15 min. Two dummy scans were performed prior to the image acquisition to eliminate signals arising from progressive saturation.

2.5. fMRI data analysis

All pre-processing steps and statistical analyses were carried out using SPM8 (http://www.fil.ion.ucl.ac.uk/spm/software/spm8/). Prior to pre-processing, the first three volumes of each run were discarded. For each participant, functional images were spatially aligned and slice-time corrected to the first volume of the first run, and then normalized to the EPI template brain. The normalized functional images (resampled at 3 mm^3) were spatially smoothed with a Gaussian kernel of full width half-maximum of 8 mm^3. A 128s temporal high pass filter was applied to remove low-frequency scanner artifacts. Using a first-order autoregressive model (AR-1), temporal autocorrelations were estimated using restricted maximum likelihood estimates of variance components, and maximum likelihood estimates of the activations were formed using the previously resulting non-sphericity.

In statistical analyses, we constructed models of six regressors coding for onsets and durations (2 s) of FIT, FMT, FB, TIT, TMT, and TB. The regressors were convolved with SPM8's canonical hemodynamic response function (HRF) and the models were regressed against the observed BOLD data. As in the previous study of Tu, Qiu, et al. (2013), the fMRI activations of FIT, FMT, TIT, and TMT consisted of three cognitive processing components: cue, masked tool pictures, and modulation of the processing of the masked tool pictures by the cue. Next, analyses focused on category-selective attentional modulation on masked invariant tool pictures [(TIT − FIT) − (TB − FB)] and on masked variant mirror-image tool pictures [(TMT − FMT) − (TB − FB)] at an uncorrected threshold of $p < .005$ (cluster size > 50 voxels). The activity (right MOG) was then corrected at a small volume (occipital gyrus) FWE corrected threshold of $p < .05$. The analyses included FB and TB conditions for excluding the pure top-down effects without the stimuli.

3. Results

3.1. Masked target visibility test

The participants reported not being able to recognize the masked tools. However, all of them reported being able to sense the changes of contours and orientations under the condition of the masked variant mirror-image tool pictures, and could sense the contours and orientations under the condition of the masked invariant tools. All 20 participants scored at chance level (binomial test, $p > .05$) for the forced-choice task, suggesting that participants were unable to recognize the masked tools. Also at the group level, discrimination performance did not deviate from chance level either (mean percentage correct = 50.03%, SD = .08, $t(19) = .16$, $p > .05$). These results suggested that participants could not consciously recognize the masked tool stimuli and were only partially aware of them.

3.2. Behavioral results

The accuracy rates of consistent and inconsistent trials (i.e. whether or not a supraliminally presented picture at the end of a trial matched the category cue at the beginning of a trial) were: 97.1 ± 4.1% (TIT), 97.9 ± 2.4% (TMT), 97.5 ± 3.3% (TB), 99.2 ± 1.5% (FIT), 98.3 ± 2.6% (FMT), and 98.5 ± 2.2% (FB), respectively. A two-way repeated-measures ANOVA with cue (tool vs. face) and target (IT vs. MT vs. blank screen) as factors revealed that neither of the main effects reached statistical significance, $F(1, 19) = 3.13$, $p > .05$, $\eta_p^2 = .14$ for the cue, and $F(2, 38) = .06$, $p > .05$, $\eta_p^2 = .00$ for the target. Nor was there a significant interaction between the two factors $F(2, 38) = 1.88$, $p > .05$, $\eta_p^2 = .09$.

We then calculated RTs only for correct trials, including both consistent and inconsistent trials. The RTs were (mean ± SE): 837.61 ± 25.56 ms (TIT), 833.63 ± 24.61 ms (TMT), 837.29 ± 26.28 ms (TB), 717.22 ± 24.26 ms (FIT), 715.54 ± 19.75 ms (FMT), and 717.57 ± 21.27 ms (FB), respectively. A two-way repeated-measures ANOVA, using cue (tool vs. face) and target (IT vs. MT vs. blank screen) as factors, revealed a main effect of cue, $F(1, 19) = 59.06$, $p < .05$, $\eta_p^2 = .76$, demonstrating that participants exhibited significantly faster RTs to face than to tool cues. In contrast, the main effect of target did not reach statistical significance, $F(2, 38) = .16$, $p > .05$, $\eta_p^2 = .01$, nor was the interaction between the two factors significant, $F(2, 38) = .02$, $p > .05$, $\eta_p^2 = .01$.

3.3. fMRI results

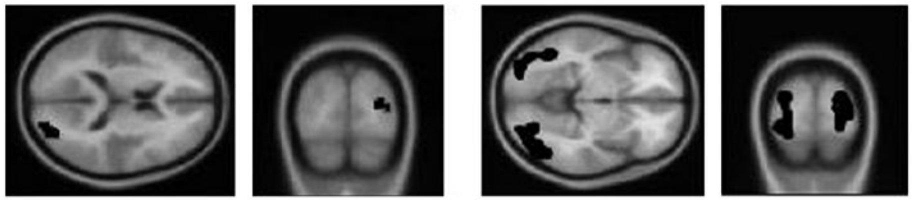
Analyses of category-selective attentional modulation on masked invariant tool picture processing showed decreased activity in the right MOG ($x = 30$, $y = -81$, $z = 12$; and $t = 3.47$) at an uncorrected threshold of $p < .005$ (cluster size > 50 voxels) after a whole-brain analysis [(TIT − FIT) < (TB − FB)], which disappeared when using a whole-brain correction. We then corrected the MOG activation from the uncorrected threshold result using a small volume FWE correction in the whole occipital cortex (standard brain atlas) at a threshold of $p < .05$ and the activity survived under the tool selective attention compared with the face selective attention condition (Figure 4). The analyses of category-selective attentional modulation on masked variant mirror-image tool picture processes revealed neither positive nor negative changes in activity in the occipital gyrus at an uncorrected threshold of $p < .005$ (cluster size > 0 voxels) under tool selective attention compared with face selective attention condition [(TMT − FMT) = (TB − FB)], even at an uncorrected threshold of $p < .01$ (cluster size > 0 voxels).

To see whether the effects were constrained to the unilateral visual cortex or not, using a liberal uncorrected threshold of $p < .05$ (cluster size > 100 voxels), we observed a bilateral decrease in activity for masked invariant tool pictures in the visual cortex under the tool selective attention compared with the face selective attention (Figure 4). All results were visualized using xjView toolbox (http://www.alivelearn.net/xjview).

To obtain more information regarding the last two comparisons, we extracted the percent signal change for each conditions (TIT, FIT, TMT, FMT, TB ,and FB) in a ROI sphere with a center at $x = 30$, $y = -81$, $z = 12$, and a radius of 5 mm using Marsbar toolbox. The percent signal changes were (mean ± SE): .079 ± .016 (TIT), .073 ± .015 (FIT), .080 ± .018 (TMT), .058 ± .014 (FMT), .091 ± .017 (TB), and .065 ± .016 (FB), respectively (see Figure 1(B)). As our discussion refers to the combined results of this study and Tu, Qiu, et al. (2013), the MOG activity of TDT (Tool-cue/masked-Different-Tool), FDT (Face-cue/masked-Different-Tool), TB (Tool-cue/masked-Blank-screen), and FB (Face-cue/masked-Blank-screen) conditions in Tu, Qiu, et al.'s (2013) study was also extracted. The location of the ROI for signal extraction was the same as in this research for accuracy of comparison. The percent signal changes were (mean ± SE): .421 ± .046 (TDT), .328 ± .032 (FDT), .377 ± .041 (TB), and .332 ± .035 (FB), respectively (see Figure 1(A)). We can see that the difference between TB and FB in Tu, Qiu, et al. (2013) (Figure 1(A)) showed a pattern similar to that in the present study (Figure 1(B)), i.e. TB > FB, and the modulation activation in the MOG increased successively as the changes of contour/shape of the masked tool pictures increased: (TIT − FIT) < (TB − FB) for masked invariant tool picture, (TMT − FMT) = (TB − FB) for masked variant mirror-image tool picture, and (TDT − FDT) > (TB − FB) masked variant different tool picture.

In addition, the contrast comparing the difference between (TIT − FIT) and the difference between (TMT − FMT) was also significant using percent signal change [$t(19) = -2.21$, $p < .05$], with (TIT − FIT) being smaller than (TMT − FMT) (see Figure 1(B)). Further, a two-way ANOVA with cue and masked stimuli as factors showed that the main effects and the interaction were all significant: cue, $F(1, 19) = 15.74$, $p < .05$, $\eta_p^2 = .48$; target, $F(2, 38) = 4.63$, $p < .05$, $\eta_p^2 = .21$; interaction, $F(2, 38) = 3.35$, $p < .05$, $\eta_p^2 = .16$. The simple effects revealed that effects of the masked stimuli were significant under both cues, $F_s > 3.38$, $p_s < .05$. Specifically, the *post hoc* test showed that there is no difference between the three masked stimuli (DT, IT, B) under each cue (F, T) except FIT > FMT, TB > TIT, and TB > TMT (Figure 1(B)).

Figure 4. Statistical parametric maps for different threshold and cluster size.



Notes: Left column: (TIT − FIT) < (TB − FB). Statistical parametric maps were displayed at an uncorrected threshold of $p < .005$, cluster size > 50 voxels. However, the activation was also significant at $p < .05$ (small volume FWE correction in the whole occipital cortex). When processing masked invariant tools, activation in the right MOG decreased under the tool-selective attention compared with the face-selective attention condition. However, when processing masked variant mirror tools, neither positive nor negative changes in activity in the occipital gyrus was shown at an uncorrected threshold of $p < .005$ (cluster size > 0 voxels). Right column: Statistical parametric maps were threshold at $p < .05$, cluster size > 100 voxels (uncorrected). When processing masked invariant tools, decreased bilateral activities were shown in the extensive occipital gyrus.

4. Discussion

Tu, Qiu, et al. (2013) found that the modulation activation in the MOG under a masked face condition decreased under face-selective attention compared with tool-selective attention, i.e. (FF − TF) < (FB − TB), which was consistent with the predictive coding theory. However, they also found an opposite pattern of results in the masked tool condition which indicated that the modulation activation in the MOG increased under tool-selective attention compared with face-selective attention, i.e. (TDT − FDT) > (TB − FB), which contradicted the predictive coding theory. In the present fMRI study, we investigated whether the opposite effects of top-down category-selective attentional modulation observed in the masked face and tool conditions in Tu, Qiu, et al. (2013) were due to the changed contours of the tools at the partial awareness level. Consistent with this suggestion, the present results revealed that, in the IT condition, the modulation activation in the MOG decreased under the tool selective attention compared with the face selective attention condition, i.e. (TIT − FIT) < (TB − FB), which was similar to the result of the completely unconscious face condition in the Tu, Qiu, et al.'s (2013) study. Interestingly, however, in the MT condition, the modulation activation in the MOG revealed neither positive nor negative changes at a very liberal threshold, i.e. (TMT − FMT) = (TB − FB). Combined with the result of increased modulation activation in the MOG in the different tool condition in Tu, Qiu, et al. (2013), i.e. (TDT − FDT) > (TB − FB), the three different modulation effects under IT, MT, and DT conditions (Figure 5) demonstrated that not only could the unconscious component of partial awareness processing (meaning of the tool) be modulated by the category-selective attention in the earlier visual cortex but also that the modulation could further interact with the conscious component of partial awareness processing (the changing contours of the tool) in a continuous manner (modulation activation in the MOG was from deactivation to no changes, and to increased activation). We discuss these results in detail below.

Some studies have found that visual areas are sensitive to repetition suppression (Weigelt, Muckli, & Kohler, 2008) and that repetition suppression effects occur only when the same exemplar of a category is repeatedly presented, but not when different exemplars are presented (Chouinard, Morrissey, Köhler, & Goodale, 2008). However, in this study, because the repetition suppression is assumed to influence both the cue/target congruent and the cue/target incongruent conditions equally, the potential repetition suppression should not have undermined our conclusion that the results reflect the interaction between category-selective attention and masked tools processing.

In addition, the present results suggest that the processing of the masked tools is at a partial awareness level. As noted in the introduction, partial awareness is an intermediate level between a completely conscious and a completely unconscious representation of information, with each representation level accessible independently from the other (Kouider et al., 2010). In this experiment, participants could sense the contours of the masked tools but could not recognize them. In other words, participants were unconscious of the identity of the tools but conscious of some features of the tools. The dissociation between the above two levels of processing and their interaction with category-selective attention can explain the continuous changes of modulation activation in the MOG.

We draw two conclusions from this study. Firstly, in the IT condition, the modulation activation in the MOG decreased under the tool selective attention compared with the face selective attention condition. This finding is consistent with the predictive coding theory (Rao & Ballard, 1999), according to which the brain estimates visual inputs with predictions from top-down signals, and tries to

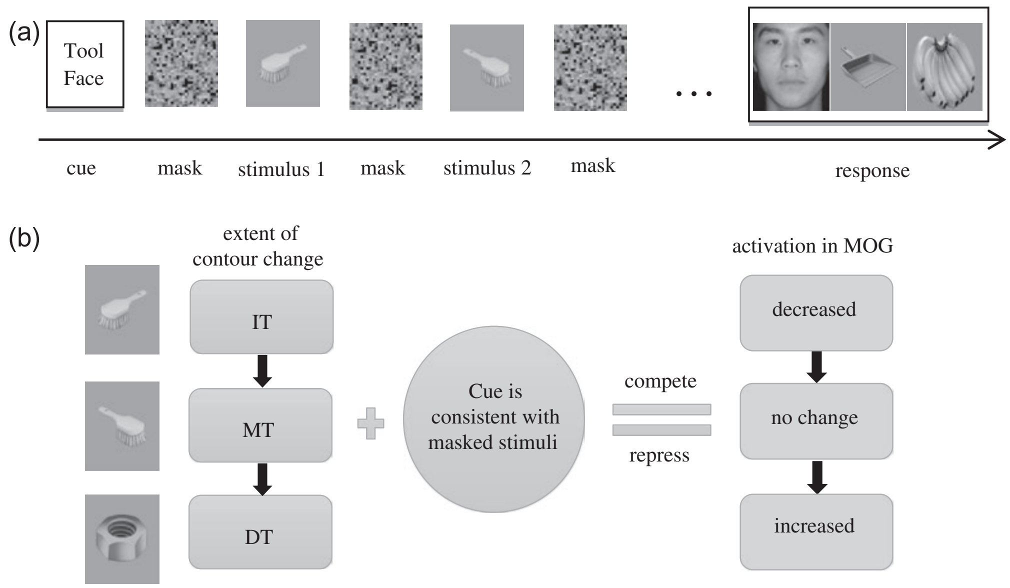


Figure 5. Summary of three conditions: (a) schematic illustration of stimulus displays; (b) summary of the results of the three conditions (IT = masked invariant tool picture; MT = masked variant mirror-image tool picture; DT = masked different tool picture).

Source: Modified from a review paper by Tu and Zhao (2014).

reduce the mismatch between them. Similar results from other studies (that activation in lower visual areas is reduced when the stimuli are predictable or more coherent) are also consistent with predictive coding theory (Alink, Schwiedrzik, Kohler, Singer, & Muckli, 2010; Cardin, Friston, & Zeki, 2011; Kok, Jehee, & de Lange, 2012). Likewise, Kiefer and Martens (2010) proposed the attentional sensitization model which can also explain top-down modulation on unconscious processing (Martens & Kiefer, 2009; Naccache, Blandin, & Dehaene, 2002; Shin, Stolte, & Chong, 2009). However, these results are primarily from conscious processing studies. For an investigation of this issue at the unconscious level, Tu, Qiu, et al. (2013) revealed that activation in the MOG, which reflected the category-selective attentional modulation on completely unconscious face picture processing, decreased under the face selective attention compared with the tool selective attention cue. Similarly, attentional load, which is measured by the attention demand of a central task and can be regarded as an irrelevant top-down factor, is also found to modulate the responses to unconscious stimuli in the primary visual cortex (Bahrami et al., 2007). Therefore, the predictive coding theory might also be applied to unconscious processing, and hence it is reasonable to suggest that top-down category-selective attention can modulate the unconscious component of partial awareness as well in the earlier visual cortex.

Secondly and interestingly, in the MT condition, the modulation activation in the MOG revealed neither positive nor negative changes in activity across the two category cue conditions. On the other hand, Tu, Qiu, et al. (2013) have found increased modulation activation in the MOG during a masked *different* tool picture presentation, and hypothesized that the incongruity caused by changed tool contours at the partial awareness level leads to excessive activation in the MOG when the unconscious meaning of the tool is consistent with the cue. The excessive activation hypothesis was supported by findings from a recent ERP study using a similar paradigm to the present one but with only one presentation of the masked stimulus in a trial (Liu et al., 2015). The ERP results demonstrated that, regardless of whether the masked stimulus was completely or partially unconscious, C1 component was smaller in the consistent cue condition than in the inconsistent cue condition. However, based on the combined results of the three conditions from this study and Tu, Qiu, et al. (2013) (invariant tool contour, mirror-image tool contour, and different tool contour, Figure 5), the excessive activation hypothesis can be expanded into a more general one which posits that not only can the category-selective attention modulate the unconscious component of partial awareness processing but the modulation effect can further interact with the conscious component of it as well in a continuous manner (Figure 5). Specifically, category-selective attention reduced MOG activation caused by the unconscious "meaning" of the tool targets when cue and targets were congruent. On the other hand, the MOG activation increased with the increase in the change of contours which is consistent with the finding that activation in V1/V2 areas decreased with increased stimulus "collinearity" and that activation in the middle occipital cortex decreased with increased "meaning congruency", and vice versa (Cardin et al., 2011). More importantly, the MOG effect caused by the change of target contours interacts in a continuous manner with the top-down category-selective attentional modulation on the unconscious "meaning" of the tool targets: the more incongruity in the changed pattern that was generated by the variant tool contours at the partial awareness level, the more excessive activation in the MOG occurred when the unconscious "meaning" of the tool was consistent with the cue (however, the contour manipulation in the masked tool condition, i.e. the normal vs. its mirror image, might not have been large enough to cause the signal change in the TMT condition to deviate from that of the TIT condition). On the other hand, the more congruity in the changed pattern generated by the variant tool contours at the partial awareness level, the more deactivation in the MOG when the unconscious "meaning" of the tool is inconsistent with the cue (see the point corresponding to FMT in Figure 1(B)). We suggest that the seemingly continuously changed modulation activation in the MOG is caused by the interaction between the extent of the changed contour at the partial awareness level and the top-down modulation of the unconscious meaning of the tool targets.

Casali et al. (2013) recently discovered a quantitative/continuous measure of the level of consciousness with EEG called the perturbational complexity index (Casali et al., 2013). Similarly, Kouider et al.'s (2010) the partial awareness hypothesis postulates that access to consciousness could be graded. Unfortunately, the quantitative/continuous notion of consciousness is seldom used in fMRI studies, leading to dichotomizing the fMRI research into unconscious and conscious domains of studies. The possible exceptions are studies using varied attentional loads (Lv et al., 2010). For example, Bahrami et al. (2007) found that responses to the unconscious stimuli in the primary visual cortex decreased significantly under high attentional load compared with low attentional load in the central task. As noted above, attentional load is measured by the demand of a central task and thus can be regarded as an irrelevant top-down factor as should also have been the case in the inconsistent conditions (FIT or FMT) of the present study. So far, not enough attention is given to the quantitative/continuous notion of consciousness in current fMRI studies. The findings of continuous changes of modulation activation in the MOG in this study can hopefully provide a needed impetus to encourage conceptualizing consciousness as a quantitative/continuous construct in future fMRI research on consciousness.

Finally, although we have interpreted our results as supporting the "excessive activation" and "continuous manner" hypotheses, these hypotheses might be better assessed in future studies by testing three conditions in an experiment, i.e. an invariant tool picture condition, a variant mirror tool picture condition, and a different tool picture condition without the category cues. Under the present design, the information provided by the category cues cannot be separated from information potentially originating from the signal change of the masked stimuli. In addition, especially relevant to the issue of the "continuous nature of consciousness", future studies can include conditions in which the same tool is presented in many different orientations similar to the method employed in mental rotation experiments (Shepard & Metzler, 1971). The moderate contour change of normal vs. mirror images used in the present experiment might be the reason why the signal change in the TMT condition did not deviate much from that of the TIT condition. In a word, although the combined results showed that not only could the unconscious component of partial awareness processing be modulated by the category-selective attention in the MOG but also that the modulation could further interact with the conscious component of partial awareness processing in a continuous manner, the detail mechanism needs further investigation.

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