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From 2D to 3D: enhanced access to human conscious awareness

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Abstract

Most of our interactions with our environment involve manipulating real, 3D objects. Accordingly, 3D objects seem to enjoy preferential processing compared with 2D images, for example in capturing attention or being better remembered. But are they also more readily perceived? Thus far, the possible preferred access of real, 3D objects to awareness could not be empirically tested, as suppression was only applied to on-screen stimuli; Here, using a variant of Continuous Flash Suppression (CFS) with augmented reality goggles (“real-life” CFS), we managed to suppress both real, 3D objects and their 2D representations. In healthy young adults, real objects escaped suppression faster than their photographs. Using 3D printing, we also showed that this only holds for meaningful objects, while no difference was found for meaningless, novel ones. This suggests that the effect is uniquely mediated by affordances, shown here to be evoked by 3D objects even before these emerge to awareness.

Statement of Relevance

When it comes to visual awareness, not all stimuli are created equal. Some are more readily perceived than others, and determining which stimuli enjoy preferential access to awareness and why has been an ongoing experimental challenge. Here, we highlight a new type of stimuli that enjoy preferential access: real, 3D objects. We show that such objects are more readily perceived than 2D images, and that this effect holds only for intact, and not scrambled, objects. This not only expands our understanding of the factors affecting access to consciousness, but also suggests that affordances might play a more crucial role

in perception than previously thought. The study employs a technique that allows the suppression of actual objects placed in front of the subjects, allowing new types of questions about consciousness and its interplay with action.

Main Text

Introduction

In our daily lives we navigate in a world filled with objects, yet not much is known about the mechanisms by which real objects are processed. We do know that these mechanisms differ from ones evoked by 2D representations, both behaviorally (Ozana & Ganel, 2017) and neurally (Marini et al., 2019). 3D objects are also remembered better (Snow et al., 2014), valued more than pictures (Bushong et al., 2010), less easily habituated as a category than photographs during infancy (Gerhard et al., 2016), and learned earlier (DeLoache et al., 2003). Thus, it seems like 3D objects enjoy preferential processing over 2D images; this is strengthened by some cases of visual agnosia, where recognition of objects from pictures is impaired, while no impairment is found for real objects (*“real object advantage”*; Chainay & Humpreys, 2001). If so, could it be that humans are 'more tuned' to process real objects, akin to other stimulus types that enjoy preferential access to awareness (e.g., upright faces, socially relevant or danger-associated stimuli, for review, see Gayet et al., 2014)? If so, this would shed light both on the underlying mechanisms of object processing and on conscious perception.

In object processing, a key concept is “affordances”: motor action plans activated by objects, referring to the possible uses or actions the observer can perform on them (Gibson, 1979). Affordances are held to be automatically evoked by objects, even when either the affordances (Vainio et al., 2011) or the objects (Roche & Chainay, 2017; for review, see Borghi & Riggio, 2015) are task-irrelevant. Similarly, increased activation in areas related to functional object and tool manipulation was found also for objects for which no action is required (for a meta-analysis, see Ishibashi et al., 2016). Such activations were even claimed to occur in response to unconsciously presented tools (Fang & He, 2005; Tettamanti et al., 2017), yet other studies challenged these claims (Rothkirch & Hesselmann, 2018). Thus, it is currently unknown whether affordances can be activated at the pre-conscious level (either unconsciously or just prior to emergence to awareness, Stein et al., 2011), and if such activation facilitates conscious processing of the afforded object.

To-date, there is only suggestive evidence in that direction: one study (Gomez et al., 2017) reported enhanced attentional capture by 3D objects flankers compared with photographs flankers (akin to Eriksen & Eriksen, 1974). Critically, this effect was not found when the real objects were positioned either out of reach or behind a transparent barrier, a common manipulation for decreasing affordance activation (Caggiano et al., 2009). Another study (Weller et al., 2019) reported preferential access to awareness for useful tools compared with useless ones, for which subjects do not have motor knowledge.

Yet for real, 3D, objects to enjoy preferential access to awareness, they should be distinctively processed as different from 2D images at the pre-conscious level. Whether

this is the case is important also for the hotly debated argument about the functions of consciousness (Hassin, 2013; Shanks, 2017; Gayet et al., 2014). Until now, it could not have been tested, as the available methods so far did not allow researchers to even probe pre-conscious processing of 3D items. Current methods are all based on screen-presented psychophysical manipulations, and are therefore limited to 2D, on-screen stimuli (for review, see Breitmeyer, 2015), or, recently, to virtual objects (Suzuki et al., 2019). Here, we use a novel variant of the Continuous Flash Suppression paradigm (CFS; Tsuchiya & Koch, 2005) we developed, termed “Real-life” CFS (Korisky et al., 2018) to uniquely suppress real, 3D objects. In CFS, conscious perception of a target stimulus presented to the non-dominant eye is suppressed by a series of masks (‘Mondrians’) presented to the dominant eye (Tsuchiya & Koch, 2005), until the target stimulus "emerges" to awareness. In our paradigm, we use augmented reality goggles to present the series of masks directly to the subjects’ dominant eye, while their non-dominant eye is exposed to the real world in front of them. Any object placed in front of the subject could therefore be suppressed from awareness. We hypothesized that 3D objects would indeed emerge into awareness faster than their 2D photographs, and that this effect would be driven by affordances. Notably, when developing the method, we already found initial support for the first hypothesis (see Fig Supp. 1; based on data from Korisky et al., 2018).

Here, the question was addressed in a series of three experiments. Experiment 1 presented 3D objects and 2D photographs at three levels of representation (colored photograph, black and white, and contours), and subjects were asked to report as soon as

they emerge to awareness. 3D objects indeed emerged faster than 2D photographs, irrespective of representation level. We reasoned that this effect could be driven by three possible factors: (a) *affordances*, in line with the literature presented above; or - alternatively - (b) *depth*, so that 3D objects emerge faster due to monocular depth cues or lens accommodation (Ciuffreda, 1998); or - more trivially - (c) *differences in reflectivity* between the real, 3D objects which sometimes included shiny parts, and the matte-printed 2D photographs. These might induce low-level differences, known to affect interocular suppression (Tsuchiya & Koch, 2005). To arbitrate between these alternative interpretations of the results, in Experiment 2 (preregistration: <https://osf.io/wa8g6/>) object familiarity was manipulated as well. To do so, we prepared digital 3D models of the intact objects and of “scrambled” versions of them. This created novel, unfamiliar objects, for which subjects do not have prior motor knowledge, that share some of the low-level features of the intact objects. These models were then 3D-printed, and their emergence times were compared to emergence times of their 2D photographs. A marginally significant trend towards faster emergence of intact 3D objects, but not of scrambled ones, was found. Finally, in Experiment 3 (preregistration: <https://osf.io/vb95f/>), where a bigger sample size was used and the distance between subjects and stimuli was reduced (facilitating affordances processing, Kalénine et al., 2016), a clear and strong effect in the same direction was obtained. Overall, our results suggest that real, 3D objects are indeed more readily perceived, and that this is likely driven by the activation of affordances.

Methods

As the methodology was shared across the three experiments, we jointly describe it below, highlighting differences between experiments where needed. The complete data and analysis codes for all experiments are available here: <https://osf.io/mygt2/>.

Subjects

Ninety (90) subjects participated in three experiments for payment or course credit: 20 participants in Experiment 1 (14 females, mean age=24.35, SD=3.88, all right-handed; sample size in this more exploratory experiment was chosen on the basis of a common practice for exploratory experiments in our laboratory), 20 participants in Experiment 2 (13 females, mean age=23.35, SD=1.77, all right-handed; sample size was selected based on a power analysis of the effect from Experiment 1, see pre-registration: <https://osf.io/wa8g6/>), and 50 participants in Experiment 3 (29 females, mean age=24.76, SD=3.48, 47 right-handed; sample size defined by multiplying sample size of Experiment 2 by 2.5, see Simonsohn, 2015). Twenty-five additional subjects were excluded across experiments from the statistical analyses for not meeting the pre-registered (Experiments 2 & 3) or post-hoc (Experiment 1) exclusion criteria (notably, these criteria do not pertain to assessment of awareness levels, and are accordingly not exposed to regression to the mean threats; Shanks, 2017): two in Experiment 1 (accuracy lower than 75% \ failing to complete the task), five in Experiment 2 (low accuracy \ discomfort in wearing the AR headset \ technical faults) and eighteen in Experiment 3 (low accuracy \ failure to achieve fusion \ reporting on catch trials \ discomfort \ technical). All subjects signed a consent

form, and had normal or corrected-to-normal vision using contact lenses. They declared no past neurological, attentional, or mental disorders, and no current usage of psychiatric medicines. The experiment was approved by Tel-Aviv University's ethics committee.

Apparatus

The apparatus included a computer-controlled “puppet theater”, in which the stimulus object was placed, and a pair of augmented reality (AR) goggles (Epson Moverio BT200) worn by the subject. The graphics shown on the AR goggles were produced by a computer, using MATLAB (MathWorks, 2017) with Psychtoolbox (Brainard, 1997). The computer was connected wirelessly to the AR goggles.

The “puppet theater” (Figure 1a) was built as a white-painted wooden wall, 1m wide and 74.5cm tall. A window, 20cm wide and 15cm tall, was cut in the middle of the wall, 26cm from the bottom of the apparatus. Behind this window was a display box, acting as a stage. A retractable blind separated this box from the window to allow hiding of the stage between trials. Three LED strips, covered with three layers of parchment paper to avoid highlights, were used to illuminate the stage (Experiment 1: 2.75cd/m^2 , Experiment 2 and 3: 10cd/m^2). In Experiment 1 and 2, the “puppet theater” was placed 90cm from the subject, and in Experiment 3 - 60cm away, decreasing window size to 12cm X 10cm. Also, to minimize subjects' ability to rely on irrelevant cues to detect stimulus location, in Experiment 3 subjects wore passive noise-cancelling headphones (Sennheiser HD 25). White noise was played in between trials to prevent hearing the experimenter placing the target stimulus. Also, to prevent cross-talk between the eyes, a transparent plexiglass cover

was placed on top of the AR goggles, that was opaque only in the field presenting the CFS masks. Thus, no information aside from the CFS stimulation could be perceived by the dominant eye.

Additionally, in Experiments 2 and 3, four LEDs were set at the corners of the window of the "puppet theater". These LEDs assisted the subject in aligning her gaze with the window despite the dim lighting.

Figure 1. The setup, paradigm, and types of stimuli used in the experiments. **a** The “puppet theater” device, placed in front of the subject. The subject lays her head on a chin rest, wearing the AR goggles, and responds using a mouse (adapted with permission from Korisky et al., 2018). **b** Time course of a trial in Experiments 1, 2 & 3. Leftmost column shows the state of the “puppet theater”, middle column shows the information presented to each eye, and rightmost column illustrates subjective perception. **c** Examples of stimuli used in Experiment 1, showing one of the items in all four representation levels. **d** Examples of stimuli used in Experiments 2 & 3, showing both levels of both variables - intact vs. scrambled, 2D vs. 3D.

Stimuli

On-goggles stimuli

Using the goggles, the subject was presented with a fusion frame (Approximately 9.6x6.4 Degrees of Visual Angle (DVA), depending on individual eye disparity) and a fixation cross. During the trial, the “real-life” CFS method, described in detail elsewhere (Korisky et al., 2018), was used by presenting the Mondrians at 10Hz on the goggles, monocularly, to the dominant eye. The Mondrians were images comprised of colorful circles ranging between 0.12 and 0.84 DVA, randomly placed. The circles were of six different colors, all of 100% value and saturation in the HSV scale.

Real world stimuli

In Experiment 1, Eleven real-life common everyday objects, smaller than 15x10cm and easily recognizable, were used (SOM Fig 3). The “Color Photograph” stimuli were created by taking photographs of the objects with a Canon 700D camera, from both the left and right side of the stage of the “puppet theater”, and at the same distance as they were presented in the experiment, to match the two perspectives in which it appeared to the subject. The photographs were then professionally manipulated by a digital print designer and printed on matte paper (Epson enhanced) to avoid highlights reflection. The resulting cutouts closely matched the real objects in appearance (SOM Fig 3). The “black and white” stimuli were created by reducing the saturation of the colored photographs to zero. The “contour” stimuli were created by employing a “find edges” filter on the “black and white” stimuli (Photoshop, Adobe Inc.).

In Experiment 2, two sets were used (for creation process, see SOM): "Intact" stimuli were ten full-color real-size 3D printed replicas of ten objects out of the eleven used in Experiment 1, all smaller than 10x10cm. "Scrambled" stimuli were 3D printed versions of these same ten objects, after being digitally deformed in various ways (see again SOM) to create meaningless non-objects. The same procedure as described above was used to prepare 2D representations of all 3D printed models. In Experiment 3, eight out of the ten stimuli were used (excluding the Rubik's cube, camera, that were too large to fit in the smaller window).

Procedure

Experiment 1 included two blocks of 88 trials, showing all eleven objects in all possible experimental conditions: representation level (Real object \ color photograph \ Black and white photograph \ contours photograph) X side of stage (left\right). Trial order was pseudo-randomly set, with the constraint that no value of one of the variables, or combination thereof, would repeat for more than three consecutive trials.

Experiment 2 included two blocks of 80 experimental trials, showing five intact objects and five scrambled objects in all possible experimental conditions: dimensionality (real 3D object \ 2D color photograph) X side of stage (left\right). To prevent subjects from forming associations between the scrambled and intact versions of the items, each subject saw each item as either intact or scrambled, but never both. Five catch trials were added to each block, where no stimulus was introduced. This was done to minimize false reports of seeing

a stimulus on one side, based on seeing the other, empty side of the stage. The maximum duration of catch trials was 19.6s in Experiment 2 and 40s in Experiment 3.

Experiment 3 was similar to Experiment 2, except for the following changes: (a) there were only 1-2 catch trials in each block; and (b) item assignment as intact or scrambled was counterbalanced between subjects, such that each item had approximately the same number of subjects exposed to it as intact or as scrambled.

At the beginning of each block, a short calibration session was conducted to account for differences in subjects' eye disparity (for details, see Korisky et al., 2018). All experiments started with a training block of up to 10 trials, using different stimuli than the ones used in the experimental trials.

Before each trial, the experimenter pulled up a blind, hiding the "puppet theater" stage, and placed a stimulus either on the left or on the right half of the stage. A fixation frame with a white background was subsequently presented binocularly for 2s. Then, Mondrians were presented to the dominant eye for 1s, while the non-dominant eye's fixation frame remained white. Within this second, the blind hiding the stage collapsed, exposing the stage to the subject. Importantly, due to the effective opaqueness of the white background and CFS masks, the subject was not yet exposed to the stimulus. Then, the white background of the fixation frame was linearly transformed to black over one second, exposing the non-dominant eye to the stage. The Mondrians were presented to the dominant eye until subjects responded, or for a maximum window of 18.6s (Experiment 1), 19.6s (Experiment 2), and 60s (Experiment 3), including the one second of opaqueness ramping-down. Subjects were

asked to report the location of the stimulus by pressing the right/left mouse button as soon as they detected it. Then, the Mondrians disappeared, allowing the subject to see the stage clearly. The blind was lifted by the experimenter, and a new trial began.

Statistical analysis

Results across the entire paper were FDR corrected (Benjamini & Hochberg, 1995), collapsing across experiments, unless otherwise specified. Overall, 16 p-values were corrected using FDR. Results in the SOM were FDR corrected separately (87 p-values). Due to the non-normal nature of the emergence time distributions in our experiments, randomization procedures and tests were employed (notably, this approach was chosen following consultation we received after the preregistration of Experiment 2; for a detailed description of the original analyses we planned, and the results obtained under these analyses, see SOM). Each such procedure or test included 10^4 iterations of resampling or reshuffling of the data, respectively. In cases where 10^4 iterations did not suffice to produce a p-value greater than zero in a test, i.e., no permutations yielded an effect as extreme as in the real data, we reran the permutation test with more iterations (10^5), in an attempt to obtain a more accurate p-value. If this too yielded a p-value of zero, we reported it as $p < 10^{-5}$.

Descriptive statistics – confidence intervals

To obtain confidence intervals (CIs) for the statistics mentioned in the paper, a bootstrapping procedure was used. A resampling of trials was done in each iteration,

respecting the division into subjects, items and conditions (i.e. not shuffling across the borders defined by the values of these variables), not including stage side (left\right). The statistics were then calculated on the resulting resampled data. The 2.5 and 97.5 percentiles of the resulting distributions were taken as Cis.

Experiment 1

Main effect of representation level. An omnibus nonparametric permutation test was conducted. The statistic calculated on the real and permuted data was the sum of squares of the differences between the average emergence time for each representation level and the overall emergence time across levels. To obtain the distribution of the null hypothesis, whereby representation level has no impact on reaction time, permutations were performed in two different fashions: First, “Per Subject Swap”: all trials belonging to a specific representation level were grouped, and their label was randomly shuffled, respecting the division into subjects and items (e.g., for a specific subject, all black and white trials in which a light bulb appeared were labeled as contour trials, and so on). Second, “Across Subjects Swap”, which was identical to the first permutation method, but applying the changed label for all subjects (e.g., all black and white trials in which a light bulb appeared were labeled as contour trials for all subjects, and so on). This shuffling type takes variance common to subjects and items into account, but does not allow for item-by-item analysis (see SOM).

To make sure the effect does not depend on specific items, a post-hoc item-based analysis was conducted under the Per Subject Swap approach. For each item, all trials in

which other items were presented were excluded from the data, and the same omnibus test was performed. Items were considered "extreme" if their per-item main effect for representation level was extreme in their distribution, and if this extremeness survived a "local" FDR correction, which included only the p-values of the per-item effects of this experiment. These extreme items were then excluded, and the grand omnibus test was performed again, to test if the effect is still obtained without them (See SOM). For the FDR correction of the entire SOM section, the original, non-locally-FDR-corrected p-values of each item's effect were used.

Paired representation level categories post-hoc comparison. To test differences between specific representation levels, the analysis was performed by excluding all trials of other representation levels. Then, the test statistic was the difference between the mean emergence times across stimuli and subjects for the two representation levels, using the same permutation procedure performed in the omnibus test.

Experiments 2 and 3

Interaction between intactness and dimensionality. A directional nonparametric test was used. The statistic was calculated by subtracting the mean difference between the two dimensionality levels (3D minus 2D) for intact items, from the same difference for scrambled items, respecting the division between subjects and items. In the permutation procedure, all trials belonging to the same dimensionality level were grouped, and their labels were randomly shuffled (2D\3D). Additionally, the labels of items as

intact\scrambled were shuffled, respecting the division between subjects and the counterbalancing (or lack thereof) between them.

Simple effect of dimensionality within each intactness level. This analysis was exploratory, and was conducted separately for intact and scrambled items. The statistic was the mean difference in emergence time between the two dimensionality levels (3D minus 2D), respecting the division between subjects and items. In the permutation procedure, it was determined with a probability of 0.5 if the labeling of all the trials of each item as “3D” or “2D” should be inverted, again respecting the division between subjects and items. Here, too, we tested to see whether the simple effects for dimensionality were driven by any one specific item (see SOM).

Main effect of dimensionality. This test was done similarly to the above test for the simple effect, except that it was done across all items, irrespective of their intactness. An additional analysis was done, where variance common to subjects and items was taken into account – "Across Subjects Swap". There, in each iteration, for each item, all trials belonging to a certain dimensionality, across all subjects, were treated as one group. Then, for each item, the labels of the two groups were inverted with a probability of $p=0.5$.

Results

Trial exclusion. In line with our pre-registered criteria, trials in which subjects' response was wrong (Experiment 1: 6.85% of total trials (N=239 across all subjects), Experiment 2: 1.75% (N=56), Experiment 3: 2.2% (N=175)) or faster than 250ms

(Experiment 1: 0.17% (N=6), Experiment 2: 1.85% (N=59), Experiment 3: 1.03% (N=82)) were removed from the analysis. Trials in which the subject did not respond at all (here and thereafter, “no response” trials, Experiment 1: 7.22% (N=252), Experiment 2: 4.45% (N=142), Experiment 3: 0.98% (N=78)) were included in the analysis, taken as evidence for the suppression to last at least as long as the duration of the trial. Additional analyses were conducted when excluding these trials, to make sure they do not solely drive the effect (see SOM), and they were excluded altogether in the main analysis of Experiment 3.

Experiment 1. We compared emergence times between four different levels of representation: real, 3D objects, 2D color photographs, 2D black and white photographs and 2D contour only photographs. A nonparametric permutation analysis revealed that emergence time differed between the four levels of representations (Figure 2): real objects emerged fastest, in comparison to color photographs, black-and-white photographs and contour images (for brevity and ease of reading, all descriptive and inferential statistics in the three experiments are reported Table 1). Post-hoc permutation analyses revealed that this effect stems solely from shorter emergence times of real objects compared with each and every other representation level (all comparisons were Bonferroni-corrected for six possible comparisons between levels). No other two representation levels differed. These effects remained largely the same also when excluding no-response trials (see SOM).

Figure 2. A violin plot depicting emergence times for different representation levels in Experiment 1. Colored dots represent single subjects, with blue horizontal lines showing the group mean, and gray vertical lines depicting 95% CI obtained by bootstrapping. The shape of each violin represents the distribution of its values along the Y axis, so that wider areas are denser with observations. On top, distribution of pairwise differences between each two levels, obtained by bootstrapping, are depicted as horizontal histograms. There, red lines represent the actual differences. Distributions excluding zero represent a significant effect (asterisks denote significance, with $*** < 0.0005$).

Experiment 2. On a descriptive level, the results suggested that the difference between 3D and 2D stimuli might be restricted to intact stimuli (see Table 1, Figure 3a), yet this trend was only marginally significant and did not survive FDR correction. Post-hoc examination of the interaction did not show a significant simple effect of dimensionality neither for intact ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=-0.33\text{s}$, $\text{SD}=0.73$, $\text{CI}=[-0.74,0.07]$, $p_{\text{uncorrected}}=0.11$, $q_{\text{FDR}}=0.23$) nor for scrambled items ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=0.2\text{s}$, $\text{SD}=0.89$, $\text{CI}=[-0.18,0.59]$, $p_{\text{uncorrected}}=0.32$). A main effect of dimensionality was not found ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=-0.07\text{s}$, $\text{SD}=0.66$, $\text{CI}=[-0.34,0.22]$, Per-Subjects-Swap analysis: $p_{\text{uncorrected}}=0.65$, Across-Subjects-Swap analysis: $p_{\text{uncorrected}}=0.68$). Excluding no-response trials yielded similar findings (see SOM).

Experiment 3. A confirmatory permutation analysis revealed a clear interaction between intactness and dimensionality (Table 1; Figure 3b). Post-hoc permutation analyses confirmed that the interaction stems from a difference between 3D and 2D stimuli for intact items, such that reaction times for intact 3D items were shorter than for their 2D photographs ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=-0.91\text{s}$, $\text{SD}=2.15$, $\text{CI}=[-1.42,-0.41]$, $p_{\text{uncorrected}}<0.005$, $q_{\text{FDR}}<0.01$). This difference was not found for scrambled stimuli, so that emergence times were similar for scrambled 3D objects and their 2D photographs ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=0.33\text{s}$, $\text{SD}=2.4$, $\text{CI}=[-0.18,0.85]$, $p_{\text{uncorrected}}=0.275$). No main effect of dimensionality was found ($\text{Mean}\Delta_{3\text{D}-2\text{D}}=-0.29\text{s}$, $\text{SD}=1.74$, $\text{CI}=[-0.65,0.06]$), using the two confirmatory analyses that

were pre-registered (permuting familiarity of items per subject, "Per-Subject-Swap", $p_{\text{uncorrected}}=0.35$, or across all subjects, "Across-Subjects-Swap", $p_{\text{uncorrected}}=0.89$, See methods; in line with the pre-registration, these two comparisons were Bonferroni corrected). Excluding no-response trials yielded similar findings (see SOM).

Figure 3. Emergence times differences between 3D and 2D representations, for intact and scrambled objects, in Experiment 2 & 3. **a** Results from Experiment 2. Blue dots represent single subjects. X-axis denotes the mean difference between 3D and 2D representations of intact items. Y-axis denotes a similar measure for scrambled items. Red crosshair represents grand mean, with error bars showing the 95% CIs obtained by bootstrapping. **b** Results from Experiment 3, using the same conventions.

Table 1. Descriptive statistics and between-levels comparisons for reaction times in all three experiments. Values are presented in seconds. See Methods for confidence intervals.

Experiment 1

Representation levels mean emergence times (in seconds), SDs and CIs [2.5%, 97.5%]

Contour photos	Black and White photos	Color photos	Real objects	Main effect: representation level
6.69 (2.62) [6.41,6.96]	6.59 (2.66) [6.32,6.87]	6.78 (2.46) [6.51,7.05]	5.60 (2.29) [5.36,5.86]	p<0.0005

Between-levels differences

Contour – BW	Color - Contour	Color - BW	Contour – Real	BW – Real	Color – Real
0.09 (0.93) [-0.28,0.49] p=0.66 [†]	0.09 (1.04) [-0.3, 0.47] p=0.72 [†]	0.18 (0.72) [-0.21, 0.58] p=0.42 [†]	1.08 (1.26) [0.71,1.45] p<0.0005	0.99 (1.05) [0.61,1.36] p<0.0005	1.17 (1.15) [0.81,1.54] p<0.0005

Experiment 2

<u>Dimensionality</u>	Intactness		<i>Combined</i>	Interaction term ([intact(3D-2D)] - [scrambled(3D-2D)])
	<i>Scrambled</i>	<i>Intact</i>		
<i>2D</i>	5.29 (3.08) [5.03,5.56]	5.45 (2.93) [5.15,5.76]	5.37 (2.97) [5.17,5.57]	-0.53 (0.96) [-1.1,0.03] p=0.063 [†]
<i>3D</i>	5.49 (3.41) [5.21,5.77]	5.12 (2.77) [4.86,5.38]	5.31 (3.05) [5.11,5.5]	
<i>Combined</i>	5.39 (3.22) [5.20,5.58]	5.28 (2.83) [5.09,5.48]		

Experiment 3

<u>Dimensionality</u>	Intactness		<i>Combined</i>	Interaction term ([intact(3D-2D)] - [scrambled(3D-2D)])
	<i>Scrambled</i>	<i>Intact</i>		
<i>2D</i>	7.39 (4.81) [7.04,7.76]	8.17 (5.15) [7.8,8.55]	7.78 (4.79) [7.53,8.04]	-1.24 (2.95) [-1.96,-0.54] p=0.0096
<i>3D</i>	7.72 (4.72) [7.36,8.1]	7.26 (4.32) [6.93,7.61]	7.49 (4.37) [7.24,7.74]	
<i>Combined</i>	7.56 (4.61) [7.30,7.82]	7.71 (4.63) [7.47, 7.97]		

[†] Non-significant p-values shown uncorrected for multiple comparisons (FDR) for evaluation, though they were used for the overall correction

Discussion

Here, we show that intact, familiar 3D objects emerge into awareness faster than their 2D pictorial representations. This was found both in Experiments 1 and 3, alongside an insignificant trend in the same direction in Experiment 2. This confirms our first hypothesis that 3D objects enjoy preferential access to awareness. Critically, the advantage of 3D stimuli was not found for scrambled, unfamiliar objects that do not elicit stored motor programs for functional use - in line with our second hypothesis.

Our results thus demonstrate the importance of affordances in granting real objects higher perceptual priority (Weller et al., 2019). This puts affordances together with other high-level, semantic properties that were claimed to influence selection into awareness (for review and criticism see Gayet et al., 2014), alongside low-level, physical ones (Levelt, 1965). Arguably, affordances are more strongly activated for real, 3D objects than for their 2D photographs (Marini et al., 2019), which in turn might increase the relevance of the stimuli, making them more readily perceived. This supports the claim that interaction with our environment is one of the key organizing principles of our visual system (Gibson, 1979).

This study further suggests that the perceptual advantage of real objects is specifically mediated by *stable affordances* rather than by *variable affordances*. Stable affordances represent prior motor knowledge about possible functional interactions with a specific

object (Osiurak et al., 2017; Borghi & Riggio, 2015), and were accordingly more likely to be activated by intact objects than scrambled ones in our experiments. Variable affordances, conversely, solely rely on the physical properties of the object and on the body schema of the observer (Osiurak et al., 2017), irrespective of the function of the objects (Borghi & Riggio, 2015). Accordingly, they are evoked by novel, unfamiliar objects (Weller et al., 2019) that showed no effect in our experiments. Thus, it seems like stable affordances drove the effect we found. Notably, stable affordances are inherently confounded by familiarity, which also affects CFS emergence times (Yuan et al., 2019), so one could claim that it was familiarity, rather than affordances, that affected emergence times. Yet this is less likely, as our critical comparison is between 3D and 2D versions of the very same stimuli (that are accordingly as familiar).

Stable affordances are thought to be mediated by the ventro-dorsal visual stream (Sakreida et al., 2016), specifically the left inferior parietal lobe (Ishibashi et al., 2016), and variable affordances by the dorso-dorsal stream (Binkofski & Buxbaum, 2013). If indeed our effect as driven by affordances, this might support claims that the dorsal stream is spared during CFS (Fang & He, 2005; Tettamanti et al., 2017). However, the latter claims are based on findings that most likely represented variable - and not stable - affordances, as they did not involve functional knowledge about specific tools. In addition, more recent claims argued that these findings are merely a result of residual conscious processing, and that dorsal stream activity does not survive CFS (Rothkirch & Hesselmann, 2018). As we

did not record neural activity, our results cannot directly speak to this controversy, but they do provide suggestive evidence in favor of spared dorsal activity under CFS (Sakreida et al., 2016).

The findings might also be taken as evidence for unconscious processing of affordances; A commonly used interpretation for breaking-CFS studies is that a difference in emergence times reflects differential unconscious processing (Gayet et al., 2014). However, this logic has been criticized, mainly on the basis of inability to discern between unconscious processing and post-perceptual processing (see again Gayet et al., 2014). Although we cannot rule out this interpretation, it seems less likely here, as the difference in emergence times was about a second in Experiments 1 and 3, which is less likely to result from post-perceptual processes, and way larger than most studies in the field. Thus, our findings – to the very least – raise the possibility that affordances are indeed evoked by unconsciously perceived stimuli, hereby supporting the automaticity of affordance processing (Borghi & Riggio, 2015; Binkofski & Buxbaum, 2013). If so, this would constitute a step forward from previous studies showing activation of motor plans by unconsciously perceived stimuli (e.g. McNair et al., 2017), that might have been evoked by low-level differences between the conditions (e.g., elongation). Such low-level differences are unlikely to explain our results, because, again, we compare 2D and 3D versions of the very same objects. Two questions left open for future research are if our results can be obtained using different and possibly larger stimulus sets, and what could be

the underlying mechanism that allows subjects to differentiate between 2D and 3D items under suppression, when information is only arriving monocularly. This could, potentially, rest on monocular depth cues (for example, blur cues (Ciuffreda, 1998) or eye-movement-induced parallax).

Finally, this study joins other studies in the cognitive sciences in using more ecological, life-like stimuli and tasks. Such realism was claimed to evoke more prominent, and sometimes even different, processing than the one evoked by well-controlled representations (Shamay-Tsoory & Mendelsohn, 2019). Thus far, using such stimuli in the study of consciousness was a great challenge given the limitations of current methods. Yet the “real-life” CFS methodology provides a compelling and easy way to do so, with practically no adjustment of the real stimuli's properties, besides luminosity or contrast.

In conclusion, we present evidence for faster access to awareness of real objects as opposed to realistic photographs of them, but only when these objects are familiar to the observer. We therefore suggest that it is stored motor representations, or “affordances”, that grant real objects priority in access to awareness, emphasizing the importance of action in perception. Our findings, and the usage of real-life CFS for suppressing real, 3D objects, pave the way to future studies exploring the limits of conscious and unconscious processing of the external world.

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Author Contributions

U.K. and L.M. designed research and wrote the paper. U.K. performed research and analyzed data.

Declaration of Interests

The authors declare no competing interests

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