MEASURING CLEVRNESS: BLACK-BOX TESTING OF VISUAL REASONING MODELS

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ABSTRACT

How to measure the reasoning capabilities of intelligence systems? Visual question answering provides a convenient framework for testing the model's abilities by interrogating the model through questions about the scene. However, despite the score of various visual QA datasets and architectures, which sometimes yield even a super-human performance, the question of whether those architectures can do reasoning remains open. To answer such a question, we extend the visual question answering framework and propose the following behavioural test in the form of a two-player game. We consider black-box neural models of CLEVR. Those models are trained on a diagnostic dataset benchmarking reasoning. Next, we train an adversarial player that re-configures the scene to fool the CLEVR model. We show that CLEVR models, which otherwise may perform at a human level, can easily be fooled by our agent. Our results question one more time whether data-driven approaches can do reasoning without exploiting numerous biases that are often present in those datasets. Finally, we also propose a controlled experiment measuring the efficiency of such models to learn and perform reasoning.

1 INTRODUCTION

Are our artificial intelligence systems capable of reasoning? Or like *Clever Hans*, they use various cues only tangentially related to the task and rely on rote memorization with poor generalization? (Pfungst, 1911; Johnson et al., 2017a) This work revisits such a question and proposes an interactive framework with the communication channel between two players. The first player, which reasoning capabilities we are about to test, performs visual reasoning tasks. The second player, which we call the *Adversarial Player*, is manipulating the scene so that it *fools* the first player even though those changes still lead to correct reasoning steps among humans. Both players interact with each other only through questions, answers and the visual scene as shown in Figure 1. Since we use the visual question answering framework as the interrogation medium, assuming that both players can deal with textual questions and answers, we also call the first player the *Visual-QA Player*.

If the *Adversarial Player* manipulating the scene causes the *Visual-QA Player* to change its answer even though the new scene is still valid for the same question and answer, it is then the reasoning failure. It is similar to the following situation. Imagine a box is placed between two spheres. If you ask a question, *is there a box between two spheres?*, the answer should be positive. Now, if we move the box anywhere so it does not cross any of the spheres, and ask the same question, the response should remain unchanged. In other words, we postulate that reasoning outputs of agents need to be invariant under scene configurations that are consistent with the questions-answer pairs. Moreover, in the spirit of generic adversarial attacks (Szegedy et al., 2014; Goodfellow et al., 2015), we seek configurations that also pose little if any reasoning challenges for humans.

In this work, we propose an automatic and agnostic pipeline to benchmark the reasoning capabilities of various models. The only assumption that we make about those models is that they can perceive the scene and communicate by answering questions about the scene. Due to the recent stream of research in vision-and-language (Zhang et al., 2021; Jiang et al., 2020; Guo et al., 2019b; Su et al., 2020; Wang et al., 2020; Kamath et al., 2021; Tan & Bansal, 2019; Chen et al., 2020), we believe there will be an increasing number of vision models that can operate through language. Moreover, we also consider the visual question answering framework set-up as a two-player system as an excellent benchmarking pipeline. We perform all tests by scene manipulations and observing how

a tested model behaves under such changes. The pipeline does not require any knowledge of the internals of the tested model. It also does not manipulate the sensory information of such a model, i.e., pixels in the images, and all the manipulations are physically meaningful.

Even though our current pipeline uses synthetic scenes as only those can easily be automatically manipulated, our results have also real-world ramifications. If models are susceptible to semantically *meaningless* changes[1] in scene configurations, in a synthetic setting, there are valid concerns that real-world robots could also be prone to manipulation of objects in a room.

Finally, our work also questions the possibility of training and benchmarking networks in a purely data-driven and offline, static manner. Although most of our CLEVR models can reach a 'super-human' performance on CLEVR, they are much less-CLEVR if another agent can manipulate the scene. Our results show that those models fail on various reasoning tasks, even though a relatively simple interpolation between configurations is possible; where even no new features are introduced. We also show that the existing models may be inefficient in learning to perform reasoning.

Contributions. The main contributions of our work could be summarized in three points.

First, we propose a strong *black-box* adversarial test, which makes no assumptions about underlying mechanics of a tested model, formulated as a game between two players. Our test does not require any direct access to the tested model, even through its sensory information. In particular, it does not require gradients, output probabilities, or any access to the perceived image. Our work also deviates from bounded perturbations and instead focuses on global scene manipulations that are still consistent with the task constraints, and can change the behaviour of a tested model.

Second, we reformulate visual reasoning by integrating visual question answering with zero-sum two-player game frameworks. Under our novel formulation, a visual and adversary agents compete against each other through content manipulation. We believe that this is an initial step towards more sophisticated frameworks that integrate computer vision with multi-agent systems.

Third, we explore the limits of the data-driven approaches in synthetic visual scenarios, and demonstrate that current CLEVR models are lacking the efficiency to learn robust reasoning steps.

2 Related Work

Our work touches upon various research directions, which we briefly describe here.
Visual QA. Introduced as a visual counter-part of the Turing Test (Malinowski & Fritz, 2014; Geman et al., 2015), it became a computer vision task that requires a holistic visual understanding. Many other works have extended the task to larger datasets or videos or adversarial train-test splits (Antol et al., 2015; Agrawal et al., 2018; Tapaswi et al., 2016; Yu et al., 2019; Girdhar & Ramanan, 2019). More recently, we also observe the generalization of the task to become a part of the vision-plus-language suite of benchmarks (Lu et al., 2019; Chen et al., 2019; Wang et al., 2021). Johnson et al. (2017a) have introduced a synthetic variant of the Visual QA problem that is more focused on reasoning and the control of the experimentation. Although it was shown that traditional methods (Yang et al., 2016) are not enough to solve that dataset, newer methods can pass the human baseline on this task. Those methods are trained to operate on pixels and text directly (Santoro et al., 2017; Perez et al., 2018; Hudson & Manning, 2018; Malinowski et al., 2018; Kamath et al., 2021) or they induce programs as an intermediate representation (Johnson et al., 2017b; Mascharka et al., 2018; Yi et al., 2018). We extend this line of research by reformulating the Visual QA task as an interactive two-agents system, where we automatically test the reasoning capabilities of some methods above in the controlled setting. We also show that CLEVR under such a new setting is still an unsolved problem.
Adversarial perturbations. Szegedy et al. (2014); Goodfellow et al. (2015); Kurakin et al. (2016); Moosavi-Dezfooli et al. (2016); Carlini & Wagner (2016) have introduced early methods that can 'fool' networks by performing tiny, visually imperceptible, perturbations of the input image. Moosavi-Dezfooli et al. (2017) have also shown universal and untargeted adversarial perturbations that are more transferable than previous approaches. Most methods perform *white-box* attacks, where an adversarial model has access to the target model's parameters or gradients. In *black-box* attacks such access is removed and, e.g., only output probabilities are available (Guo et al., 2019a). Other *black-box* attacks involve the use of surrogates to estimate gradients of the real target (Papernot

[1] Changes that are consistent with the task constraints.

et al., 2017; Cheng et al., 2019) or gradient-free methods (Alzantot et al., 2018). More related to our work, Cheng et al. (2018) describe a *black-box* system, which only assumes the access to outputs, so called hard-labels, of the network for a given query. However, all the perturbations described above are continuous-based where individual pixels are changed independently. This leads to improbable images and assumes the access to the sensory inputs of the neural network. In contrary, *semantic* perturbations (Joshi et al., 2019; Zeng et al., 2019), operate on semantically meaningful chunks of the input, leading to more plausible and physically interpretable perturbations. However, they still assume a direct access to either images or ideally differentiable renderers. We can interpret our work within the adversarial perturbations framework, where the adversarial model can change the original scene by its manipulations, with zero access to the target model, including its sensory information and not limited to tiny changes but instead to semantically and globally *meaningless* modifications.

Reinforcement learning. The game between the *Visual-QA Player* and *Adversarial Player* is a zero-sum two-player game. Conneau et al. (2017) use a conceptually similar two-player game to find a better word alignment between two languages without parallel corpus. Inspired by such a problem formulation, we consider our two-player game as a tool to achieve better reasoning models. We optimize the *Adversarial Player* with Advantage Actor-Critic (A2C) algorithm (Sutton & Barto, 2018; Degris et al., 2012). Though there are two players in the game between *Visual-QA Player* and *Adversarial Player*, in experiments presented in this work, the *Visual-QA Player* is frozen. Thus, technically, simpler optimization methods used for single-player games are applicable.

Probing and measuring intelligence. Turing Test (Turing, 2009) is considered to be among the earliest works on measuring the intelligence of artificial systems. Crucially to us, it is also formulated as a two-player game with an interrogation protocol. Legg (2008) systematizes and relates notion of intelligence from different fields with the main focus on 'universality'. Similarly, Chollet (2019) investigates various attempts at defining or measuring intelligence and highlights the role of skill-acquisition efficiency. Johnson et al. (2017a) have transferred the notion of intelligence onto the visual ground and emphasize reasoning rather than universality. Nonetheless, it seems there is no a single widely acceptable dataset or a definition that encompasses our intuitions about intelligence. However, there are a few recent directions showing the lack thereof, mainly highlighting bias amplification or absence of mathematical capabilities (Hendricks et al., 2018; Bhardwaj et al., 2021; Piekos et al., 2021). Here, we are mostly interested in visual reasoning and use the visual question answering framework as a form of communication with the otherwise *black-box* system.

3 PRELIMINARIES

In this section, we explain briefly how the CLEVR dataset (Johnson et al., 2017a) is constructed and introduce our notation and definitions.

CLEVR is a synthetic visual question answering dataset introduced by Johnson et al. (2017a), which consists of about 700k training and 150k validation image-question-answer triplets. Images are artificially constructed and rendered from scene graphs – a special structure containing information about object attributes such as position or color. Such a scene graph is also used to synthesize the ground-truth question-answer pairs by expanding templates according to the depth-first-search ordering. Ambiguous scenes are rejected. Each image represents an isometric view on the scene containing from two to ten objects. There are three classes of objects: spheres, cubes and cylinders. Each object can also be either large or small and has one colour out of four (brown, purple, cyan, yellow). It can also be either metallic or rubber-made. Every object has x and y coordinates that are confined within the $(-3, +3)$ range. We use the same generation process to render modified scenes.

CLEVR models. Various models have been introduced to work with the CLEVR dataset, some even 'solving' the dataset by achieving near perfect performance. Despite of strong offline performance, we test if those models performance perpetuates in the more interactive setting where configurations of the scene could be changed. Whenever possible, we use pre-trained CLEVR models. Otherwise, we train the remaining models from scratch by making sure we achieve results similar to published accuracy numbers on the validation set. We summarize all the models in Table 1. We show the accuracy on the CLEVR dataset (*Accuracy*), indicate if an architecture is trained from scratch (*Re-trained*), briefly describe how multimodal fusion and reasoning is conducted (*Reasoning Mechanism*), and indicate any extra privileged information required during the training process (*Extra*). For instance, some models require extra access to functional programs used during the dataset generation, use scene graphs as a supervisory signal (states), or always operate on scene graphs (input-states). Otherwise the models were trained only from image-question-answer triples.

Mini-games. We formulate our problem as a *Game* between two players: *Visual-QA Player* and *Adversarial Player*. The *Visual-QA Player* takes as input question-image pairs and provide answers to such questions. Some models use states (scene-graphs) that replace images or require programs (Johnson et al., 2017a). The whole game consists of all CLEVR data points. For our purpose, we extend the notion of the *Game* into *Mini-games*. The rules of *Mini-games* are identical to the whole *Game*. The only difference is that each *Mini-game* operates on a subset of the CLEVR dataset. We define the size of a *Mini-game* by the number of datapoints that are attached to that *Mini-game*. We sample data points for each *Mini-game* randomly and mutually exclusively. *Mini-games* have analogies in the adversarial perturbations literature. *Mini-games* of size one resemble per-image adversarial perturbations (Goodfellow et al., 2015; Moosavi-Dezfooli et al., 2016) whereas a *Mini-game* that has all data pointsis similar to universal adversarial perturbations (Moosavi-Dezfooli et al., 2017). In this work, we investigate various *Mini-game* sizes but due to the sheer scale we were unable to use the whole game as the *Mini-game*. Larger *Mini-games* make the optimization process more difficult as the domain where the *Adversarial Player* needs to operate increases. The training is also much more time-consuming and a sequential process. Instead, we can train multiple players on different *Mini-games* independently and thus massively. We leave the arduous training of the universal *Adversarial Player* on the whole *Game* as a possible future direction.

Table 1: CLEVR models that we use as *Visual-QA Players*.

Model Name	Accuracy	Re-trained	Reasoning Mechanism	Extra Data
SAN (Yang et al., 2016)	72.1		Attention	
FiLM (Perez et al., 2018)	96.2	✓	Feature Conditioning	
RN (Santoro et al., 2017)	93.2	✓	Relational	
IEP (Johnson et al., 2017b)	96.9		Neural Program Induction	Programs
TbD (Mascharka et al., 2018)	99.1		Neural Program Induction	Programs
Mdetr (Kamath et al., 2021)	99.7		Multimodal Transformer Querying	States
State-Input Transformer (ours)	96.8	✓	Cross Attention	Input-States

4 ENVIRONMENT

We need to ensure that *Adversarial Players* create valid scenes that are *consistent* and *in-distribution*. Both properties are guaranteed by our environment enforcers.

Consistency. Since scene manipulation may change the answer for a given question, we need to ensure this does not happen. That is, the new scene is still *consistent* with the question-answer pair. The question-relevance enforcer achieves that by running functional programs associated with each question (Johnson et al., 2017a) on the modified scene-graph. Hence, it gets the new ground-truth answer. The enforcer rejects the new scene if that new answer differs from the previous one. In this way, it guarantees the newly generated scenes give the same answers as the original scenes on the same question. Thus, we can generate equivalent scenes containing the same objects that have identical answers for the same questions. Using that enforcer, we can test if the *Visual-QA Player*'s answers are invariant under such an equivalent class of scenes.

In-distribution. Even with the question-relevance enforcer, the *Adversarial Player* may still produce undesired outputs. For instance, it can stretch the whole scene thus violating the scene boundaries from the original CLEVR dataset, making, e.g., everything to look very small (Section A.9 in the appendix). Although it is still an interesting form of the adversarial scene manipulation, we focus rather on the *in-distribution* scene manipulations that respect the original boundaries. To enforce that property, we use scene-constraint enforcer that checks the boundaries of the scene. Without that enforcer, the *Adversarial Player* would quickly resort to stretching the whole scenes, achieving a form of adversarial attack that uses distribution shifts rather than content manipulation. It does so, e.g., by moving the camera away until objects are barely visible. We give a few such examples in the appendix (Section A.9).

5 *Adversarial Player*

In this section, we describe our *Adversarial Player* in details. Meaningful scene manipulations require not only generic scene understanding, but also the ability to distinguish which objects to

displace and how. Hence, the player is a composition of a multi-modal module, which creates input representation, and a decision maker, which decide how to manipulate the scene. In the following, we will describe that composition of modules, the game of scene manipulations, and the training protocol. Figure 1 illustrates the *Adversarial Player* and the game between both players.

Multi-modal module. We have experimented with the same multi-modal modules as those in Table 1, but found out we have a better performance and the convergence rate if the *Adversarial Player* operates on the scene-graphs (states) instead of pixels. For that, we use *state-input* variant of Relation Networks (Santoro et al., 2017). The model receives as the input $10 * 6$ object tokens, and question tokens. Every object token represents one-out-of-ten possible objects in the scene by its attributes such as position, color, shape, material and size. If the scene has fewer than ten objects, we use $\emptyset$ token to indicate that, which also acts as a padding. We also have special tokens that separate questions from the objects which we add as a latent embedding, e.g., $\text{emb}(\text{material}) + \text{emb}(\text{object})$. Such an input encoding is similar to our *State-Input Transformer* and described in Section A.3. The embedded vectors are given to the Relation Network (RN). Finally, we train that network on the CLEVR visual question answering task, where we achieve 97.6% on the validation set, and use the representation just after the last relational layer for the decision maker.

Decision maker. Inspired by the work on reinforcement learning (Mnih et al., 2016; Wu et al., 2017; Lillicrap et al., 2016; Wang et al., 2016; Schulman et al., 2015), we use an actor-critic module that acts on scenes. The actor is a general-purpose fully connected layer with ten object-specific heads. Each head is randomly assigned to a unique object in the scene for its manipulation. Every head produces a displacement in x and y coordinates of the corresponding object. Although we have initially experimented with the continuous output space, we have found out the following simple strategy is more effective. First, we discretise all the x and y coordinates into N bins each. Now, each head produces two N-dimensional vectors that are next projected into a probabilistic space via softmax. Next, we sample displacements in x and y axis independently from both softmax distributions. Note that, even though we do not model the joint distribution explicitly due to computational reasons, both samples condition on the common head and thus are only *conditionally* independent of each other. We discretise the scene where each axis has values in $[-3, 3]$ onto $N = 7$ bins per axis. Our

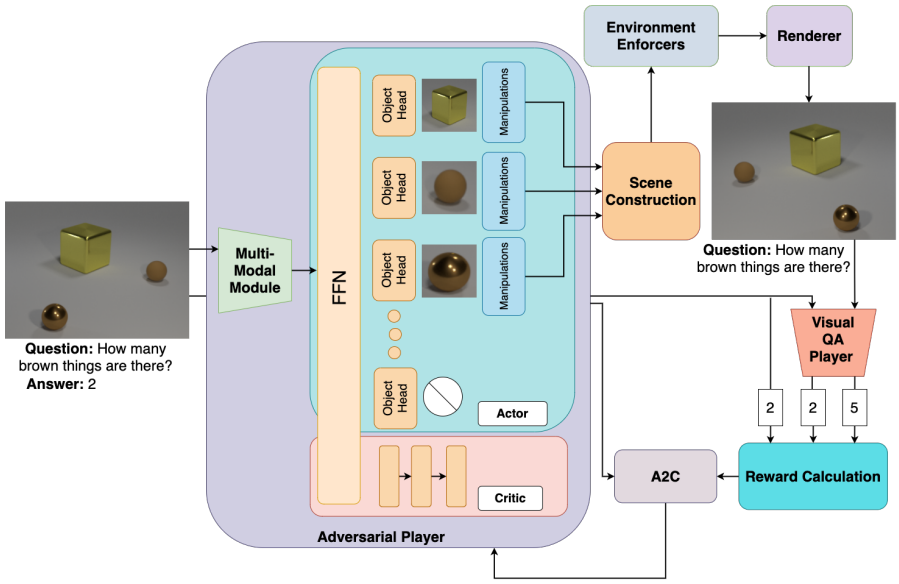

Figure 1: Our game between two players: *Adversarial Player* and *Visual-QA Player*. *Adversarial Player* uses a *multi-modal module* to extract features conditioned on the visual and textual inputs. After transforming such features with a feed-forward architecture, it samples an action using object-specific heads. Each action corresponds to manipulating the corresponding object in the scene. In the case of missing objects, we use an $\emptyset$ token. After alternating the original scene graph, we use various environment enforcers to ensure validity of the constructed scene. A valid scene graph is rendered and introduced to the *Visual-QA Player* together with the original image. Finally, we collect responses of the *Visual-QA Player* and calculate suitable rewards based on them, and we repeat the whole cycle during the training phase.

critic is a simple three layer feed-forward network (with relu as activations) that predicts a reward score between -1 and $+1$ via tanh activation ($1.2 *$ tanh for better numerical properties).

The game of scene manipulations. Due to our formulation of *Adversarial Player* and the environment, we can benchmark various reasoning models purely in the *black-box* setting via a series of questions about the scene. *Adversarial Player* manipulates the scene so that it is still consistent with the question-answer pair. The manipulations are applied to scene-graphs, and the resulting scene-graph is evaluated by the environment enforcers described in Section 4. Invalid scenes are thus discarded. In this way, we ensure the *in-distribution* and *consistency* in the scene generation. Original image-question pairs are fed to a *Visual-QA Player* that produces corresponding answers. We refer to that answers as *old answers*. After the scene manipulation, new images paired with the same questions are also given to the *Visual-QA Player* that produces *new answers*. We construct rewards based on *old answers*, *new answers* and *ground-truth answers*.

If the *Adversarial Player* forces the *Visual-QA Player* to change the answer, i.e., an *old answer* is different than a *new answer*, it gets *Consistency Drop Reward* (*cr*). If an *old answer* is the *ground-truth* answer, it gets instead *Accuracy Drop Reward* (*dr*). Both rewards differentiate between simply confusing the model and causing a drop in its performance. If *Adversarial Player* produces an invalid scene it gets *Invalid Scene Reward* (*isr*). This reward encourages producing scenes that pass the environment enforcers tests. Finally, if *Adversarial Player* does not manage to fool the model, it gets *Fail Reward* (*fr*). We use the following values: *dr*$= 1$, *cr*$= 0.1$, *fr* $= -0.1$, *isr* $= -0.8$.

Training algorithm. To train *Adversarial Player* we use the A2C algorithm with the episode length set to one as we do not need to model long-range consequences of the decision-making mechanism. Batches contain images, question, answers, programs and scene-graphs. We train the *Adversarial Player* for each *Mini-game* independently using the same architecture. We experiment with the following *Mini-game* sizes $10, 100, 1000$. All *Mini-games* are constructed randomly. Under our discretisation scheme, the action space is N^k where N is the number of bins and k is the number of objects in the scene. In practice, it is up to 49^{10}.

6 EXPERIMENTS

Main experimental results are presented in Table 2. First, we explain the terminology and this is followed by analysis of quantitative and qualitative results, additional experiments and limitations.

In our experiments, we consider *Adversarial Player* with a multi-modal module pre-trained either on states (*state-input*) or directly from pixels (*pixel-input*). As explained in Section 5, we train *Adversarial Player* for each *Mini-game* independently. We use different *Mini-game* sizes in our experiments: 10, 100 and 1000. To obtain statistically significant results, we run each *Mini-game* thirty times with randomly initialized *Adversarial Players*, each with different seed per trial. We report the results that are averaged over all those runs. We compute two metrics for each *Mini-game*. *Consistency* refers to the fraction of times *Adversarial Player* has changed the *Visual-QA Player*'s answer, regardless if that answer was correct. *Drop* refers to the fraction of times *Adversarial Player* has changed the *correct Visual-QA Player*'s answer. We aggregate the results using the following statistics. *Average Accuracy* averages accuracies over all *Mini-games*. *Maximal Accuracy* refers to the maximal accuracy over all *Mini-games* (so it refers to accuracy of a single *Mini-game*). It is the worst (best) case from the *Visual-QA Player* (*Adversarial Player*) perspective. We also computed p-values of T-Test, with the null hypothesis that a manipulation is unsuccessful. In almost all cases we reject the null hypothesis with small p-values. We only did not 'fool' TbD and MDetr, and only if *pixel-input Adversarial Player* is considered (Section A.11, in the appendix).

Quantitative results. We show our results in Table 2 for the *state-input* and *pixel-input Adversarial Players*, and for each *Visual-QA Player* presented in Table 1. All the *Visual-QA Players* in the comparison are trained from pixels, apart form our custom *State-Input Transformer* architecture (Section A.3 in the appendix). When comparing both *Adversarial Players*, we can observe that the *state-input Adversarial Player* is significantly more successful than the *pixel-input* one. We hypothesize that this is the effect of having more structured and less ambiguous input information. It could also be the case that multi-modal modules trained from pixels ignore features in the same way and hence smaller discrepancy between all models operating on pixels. Another observation is that in the case of TbD and MDetr, *pixel-input Adversarial Players* are unable to solve the smallest-size *Mini-games*. Moreover, as the size of *Mini-games* increases, it is becoming more difficult for the *Adversarial Player* to successfully manipulate the model on all examples from the *Mini-game*. It is

an expected behavior resembling standard adversarial perturbations (Goodfellow et al., 2015) and their universal variants (Moosavi-Dezfooli et al., 2017). The highest performing CLEVR models, TbD and MDetr, are the most robust under the manipulation. However, they are still susceptible to the scene manipulations in some *Mini-games* as the *Maximal Consistency* metric indicates, especially if our *Adversarial Player* uses states as the input. Section A.8 (appendix) also shows richer performance statistics. Our detailed investigation shows that the models above are particularly sensitive to manipulations of scenes associated with *counting* or *existence* questions. Questions of those types are often more complex, hence, increasing the likelihood of the reasoning failure at some stage (Section A.6 in the appendix).

Qualitative results. Figure 4 shows qualitative results of the scene manipulations for the three highest performing and distinctive models from Table 1; e.g., simple feed-forward or program induction models. For the reader's convenience, we provide in Section A.2 (appendix) examples of CLEVR object attributes. We can observe that the scene manipulations are surprisingly minimal and are semantically *meaningless*, i.e., they should not 'fool' human players.

Saturation of *Adversarial Player*. Training an *Adversarial Player* on larger *Mini-games* become an increasingly more difficult task as the player needs to operate successfully on more diverse examples. Figure 2 shows the performance of the *Adversarial Player* against *Mini-game* sizes, where FiLM, TbD, MDetr and *Input-State Transformer* (Trans.) are chosen as *Visual-QA Players*. We can see that the performance of *Adversarial Player* saturates around *Mini-games* of size 10k, which we call the *Critical mini-game size*. We use two trials for our experiments, and the *Accuracy Drop* as a metric. It measures the drop in accuracy of a *Visual-QA Player*.

Adversarial training. In initial experiments, we have adapted a widely used adversarial training (Goodfellow et al., 2018), where we include manipulated scenes in the training protocol of a *Visual-QA Player*. We use *pixel-input* RN (Santoro et al., 2017) as the *Visual-QA Player*. Using this method, we have obtained only marginal improvements in robustness at the cost of a slight performance degradation on the original CLEVR dataset.

Limitations of data-driven CLEVR models. If we can't achieve robustness under scene manipulations with the adversarial training, what fraction of all data is sufficient then? Intuitively, if the network has enough capacity, and was trained on all possible data points or its manipulations, it should rely on a look-up strategy to solve the problem accurately. We propose the following experiment to address such a question. We create a dataset containing three objects in six different starting positions and seven templated questions. We consider only object displacements on the grid 7×7, and thus $49^3 = 117649$ combinations are possible. We use RN (Santoro et al., 2017) as a *pixel-input Visual-QA Player*. We train such a model on $X\%$ data and next evaluate on $(100 - X)\%$ remaining, unseen data. We have conducted ten trials by forming $X\%$ training data randomly. Figure 3 shows that when trained on 10% of data, the model becomes resistant to 40% of unseen manipulations. The robustness of the model increases linearly, saturating at roughly 97% accuracy after observing almost all data (90%). The behaviour of all tested models is similar with slightly better overall performance of TbD. The results indicate that a lot of training examples are needed to cover most configurations of our task in the absence of stronger inductive biases.

7 Conclusions

We present a novel approach to benchmarking the reasoning capabilities of various visual models by formulating a game between two players. Both players are independent and can only communicate through a common interface: an environment and question-answer pairs. One player, named *Adversarial Player*, is trying to manipulate the environment so that the second player, named *Visual-QA Player*, can't answer the given question anymore. To test our framework, we run our game against a few popular CLEVR models that achieve solid results on the CLEVR dataset; often surpassing the human baseline. We show that such models are susceptible to scene manipulations, and their performance may degrade significantly. Moreover, we also conducted a controlled study on the generalization capabilities of such models. We did so by creating a synthetic and simplified dataset of all possible scene manipulations. We show that the existing models are not particularly efficient learners and require significantly more than 50% of all data to generalize to all possible scene configurations. One possible direction to increase efficiency could be the use of stronger inductive biases. Another to change a training paradigm that is more interactive. However, the environment is synthetic, and it could be that learning from real-world and multi-modal data is somewhat more efficient. Finally, we believe that melding two-player games with the visual question answering framework is both natural

and beneficial for testing the reasoning capabilities of various models; and potentially can also be generalized to other settings. In the long term, we plan to test such models through web interfaces.

Table 2: Results of the game with the *state-input* and *pixel-input Adversarial Players*. *Before* refers to the original accuracy of the CLEVR model, before manipulations are applied. Other columns show the results after scene manipulations, using average or maximum (worst-case manipulations) accuracies. We also report in brackets a relative drop in the performance, in percentages. All *Visual-QA Players* but *State-Input Transformer* use pixels as the input. The latter uses states as the input.

			Average Accuracy		Maximal Accuracy	
Model	*Mini-game* size	Before	State-Input	Pixel-Input	State-Input	Pixel-Input
SAN	10		61.86 (-14.2%)	63.88 (-11.4%)	28.84 (-60.0%)	43.26 (-40.0%)
	100	72.1	66.11 (-8.3%)	69.28 (-3.9%)	47.65 (-33.9%)	66.32 (-8.0%)
	1000		70.29 (-2.5%)	71.09 (-1.4%)	68.42 (-5.1%)	70.87 (-1.7%)
FiLM	10		83.98 (-12.7%)	93.69 (-2.6%)	48.10 (-50.0%)	86.58 (-10.0%)
	100	96.2	89.17 (-7.3%)	94.85 (-1.4%)	75.61 (-21.4%)	92.44 (-3.9%)
	1000		93.89 (-2.4%)	95.81 (-0.4%)	90.81 (-5.6%)	94.75 (-1.5%)
RN	10		80.52 (-13.6%)	86.48 (-7.2%)	46.60 (-50.0%)	74.56 (-20.0%)
	100	93.2	85.55 (-8.2%)	90.87 (-2.5%)	63.28 (-32.1%)	87.42 (-6.2%)
	1000		90.59 (-2.8%)	91.61 (-1.7%)	90.03 (-3.4 %)	91.05 (-2.3%)
IEP	10		84.30 (-13.0%)	94.47 (-2.5%)	48.45 (-50.0%)	87.21 (-10.0%)
	100	96.9	90.31 (-6.8%)	95.64 (-1.3%)	74.41 (-23.2%)	93.50 (-3.5%)
	1000		94.18 (-2.8%)	96.60 (-0.3%)	93.99 (-3.0%)	95.73 (-1.2%)
TbD	10		94.04 (-5.1%)	99.10 (-0.0%)	69.37 (-40.0%)	99.10 (-0.0%)
	100	99.1	96.62 (-2.5%)	98.70 (-0.4%)	91.17 (-8.0%)	98.00 (-1.1%)
	1000		98.00 (-1.1%)	99.00 (-0.1%)	95.53 (-3.6%)	98.80 (-0.3%)
Mdetr	10		93.71 (-6.0%)	99.70 (-0.0%)	59.82 (-40.0%)	99.70 (-0.0%)
	100	99.7	96.11 (-3.6%)	98.60 (-1.1%)	86.43 (-13.3%)	97.80 (-1.9%)
	1000		98.50 (-1.2%)	99.40 (-0.3%)	94.51 (-5.2%)	99.10 (-0.6%)
State	10		89.34 (-7.7%)	96.02 (-0.8%)	77.44 (-20.0%)	91.96 (-5.0%)
Input	100	96.8	94.76 (-2.1%)	96.12 (-0.7%)	92.63 (-4.3%)	95.05 (-1.8%)
Transf.	1000		95.73 (-1.1%)	96.50 (-0.3%)	95.15 (-1.7%)	95.83 (-1.0%)

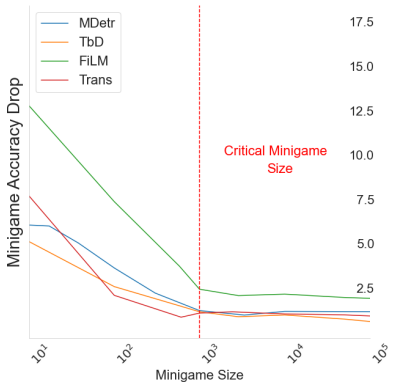

Figure 2: The performance of *Adversarial Player* with respect to *Mini-game* sizes. We use *Accuracy Drop* to measure the drop in performance of the *Visual-QA Player*. The lower the value, the less successful the adversarial manipulation is.

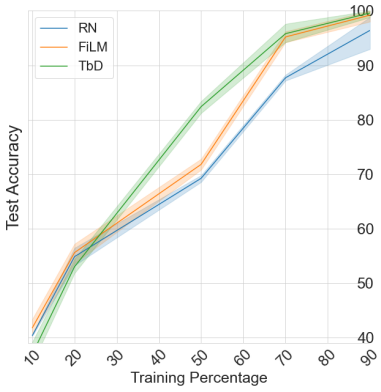

Figure 3: Performance of RN trained from pixels, on our custom dataset of all possible manipulations. We train the *Visual-QA Player* on different fractions of data (x-axis) and test on the remaining data using standard accuracy measure (y-axis).

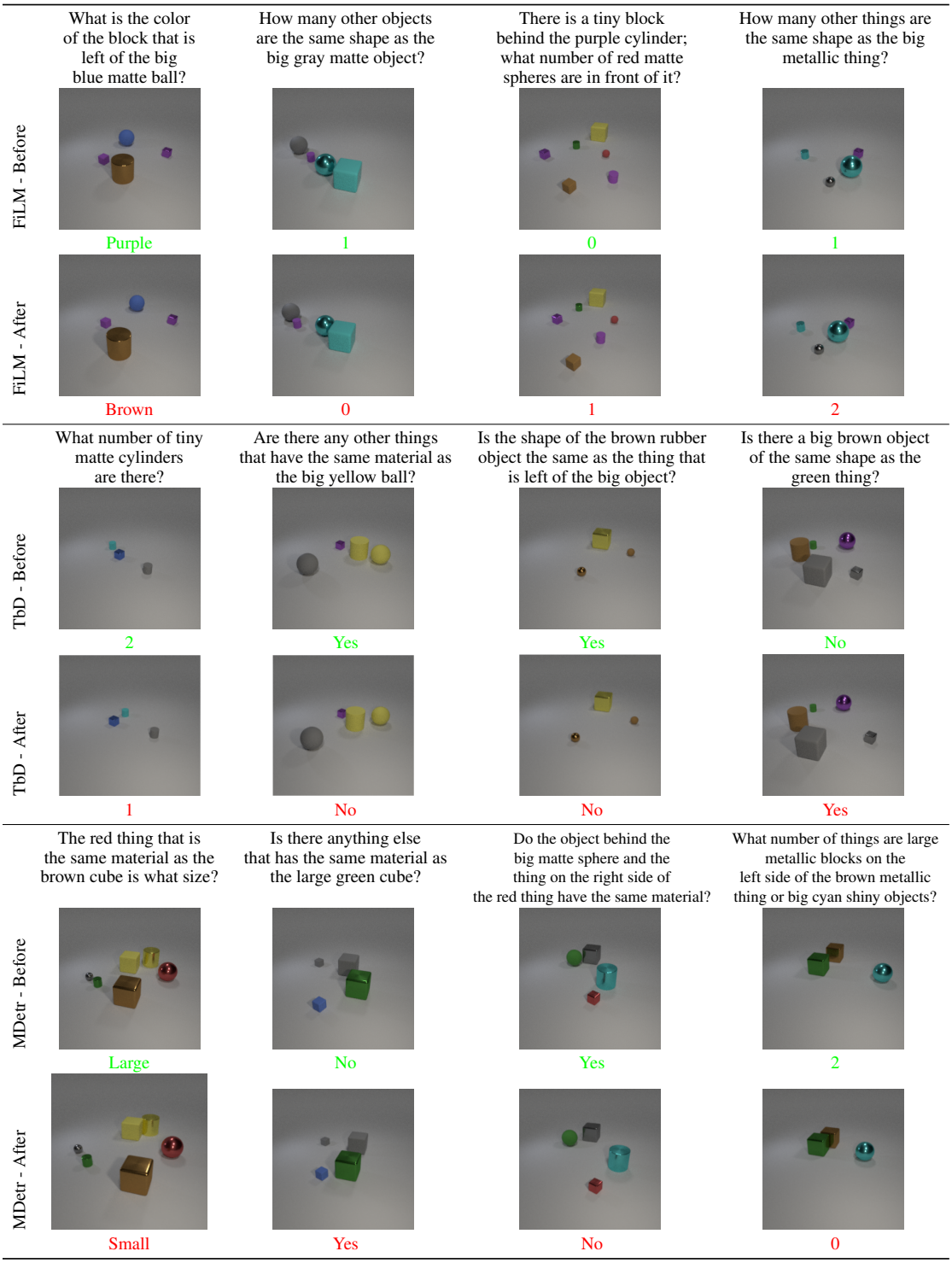

Figure 4: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

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A APPENDIX

A.1 URLS OF CLEVR MODELS

Table 3 shows the URLs to models used in our investigations (also Table 1 in the main paper). We also report if we re-trained a model from scratch (type *Architecture*) or used already trained models (type *Model*). Please note that the latter type proves that our testing procedure is fully black-box.

Model Name	Link	Type
SAN (Yang et al., 2016)	https://github.com/facebookresearch/clevr-iep	Model
IEP (Johnson et al., 2017b)	https://github.com/facebookresearch/clevr-iep	Model
FiLM (Perez et al., 2018)	https://github.com/ethanjperez/film	Architecture
RN (Santoro et al., 2017)	https://github.com/mesnico/RelationNetworks-CLEVR	Architecture
TbD (Mascharka et al., 2018)	https://github.com/davidmascharka/tbd-nets	Model
Mdetr (Kamath et al., 2021)	https://github.com/ashkamath/mdetr	Model

Table 3: URLs to Models. *Architecture* denotes that we use the code but re-trained the model on CLEVR. *Model* refers to already trained models.

A.2 OBJECT CATEGORIES

Figure 5 shows a made-up image that contains all available CLEVR object categories: shapes, sizes and materials. Small objects are rendered at approximately 40% of the size of their large counterparts. Metalic materials can be identified by the high albedo property and 'shininess' of the object. We provide it as the reference point for a reader to make it easier to compare our qualitative results.

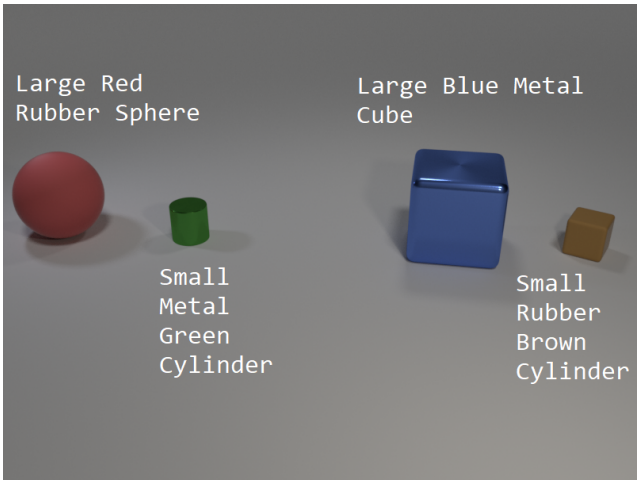


Figure 5: Object categories in the CLEVR dataset.

A.3 STATE-INPUT TRANSFORMER

To test our two-player game against a *state-input Visual-QA Player*, we have designed a transformer-based architecture Vaswani et al. (2017) that receives six types of input features – object sizes, object shapes, object materials, object colors, object positions, and question tokens – and uses a cross-modal attention mechanism. In that mechanism, queries from one modality attend to keys and values from the another modality. Since each data point contains a variable-length inputs describing the all objects in the scene as well as question tokens that compose the question itself, we do padding with a special token $\emptyset$ to the maximal input length. We set the maximal length for the objects tokens to be $10 * 6 = 60$ and 50 for the question tokens. All in all, we have 110 input tokens. Each token type is projected into a different embedding space and a learnable type embedding is added to it, separately for object and question tokens. For instance, $\text{emb}(\text{material}) + \text{emb}(\text{object})$. Furthermore, three special learnable embeddings are used as an additional input. We use them as queries to reduce the overall computational costs of the cross-attention mechanism. The same mechanism is also used in Perceiver (Jaegle et al., 2021). The input tokens (concatenated object and question tokens) form keys and values. In every transformer block, we apply cross-attention between all input embeddings and those three special tokens. This is repeated five times. As the final block, a feed-forward network (classifier) receives as inputs the three latent token and outputs answer probabilities. We show that architecture in Figure 6.

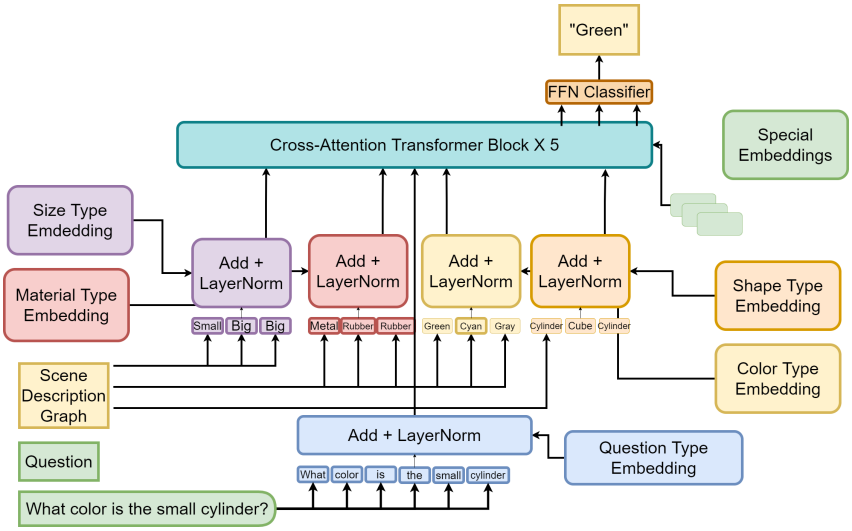


Figure 6: Our State-Input Transformer that operates on the graph scene (states).

A.4 MANIPULATIONS OF *State-Input Visual-QA Player*

Figures 7 and 8 show manipulations of *Visual-QA Player* that is trained to take *states* instead of *pixels* as the input. Such a *state-input Visual-QA Player* receives a direct overview of the scene, bypassing any need for any image renderings. We use *State-Input Transformer* (Section A.3) as the *multi-modal* component of that player. Since such a model gets the perfect visual information as the input, it makes it more robust under scene manipulations. As a consequence, our *Adversarial Player* tend to manipulate the scene so that objects are placed closely together. Often, simpler questions, which require fewer stages of reasoning, are safer to *Visual-QA Player*. Let us consider the last example in Figure 8. If the question was *What is the material of the cyan cube?*, the model would answer rightfully *metal*. Here, *Adversarial Player* 'breaks' the spatial reasoning step by creating ambiguity between the cubes and thus a wrong answer is derived.

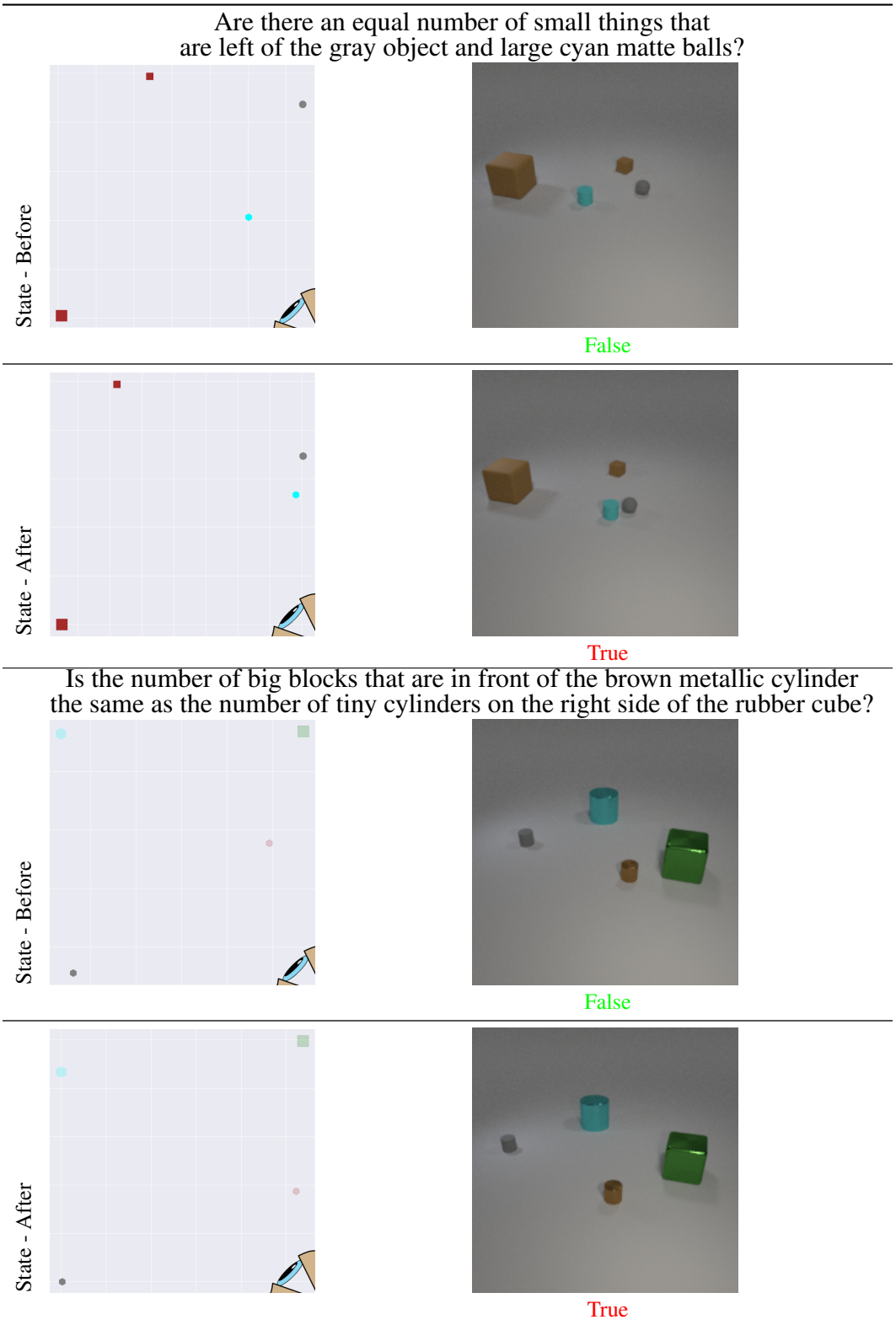


Figure 7: Qualitative results on *state-input Visual-QA Player*. For each example, a top-down view of the scene is presented. The eye at the bottom right of each view represents the rendering camera. It corresponds to the *Visual-QA Player*'s viewpoint. Each scene is also rendered and presented side-by-side for comparison.

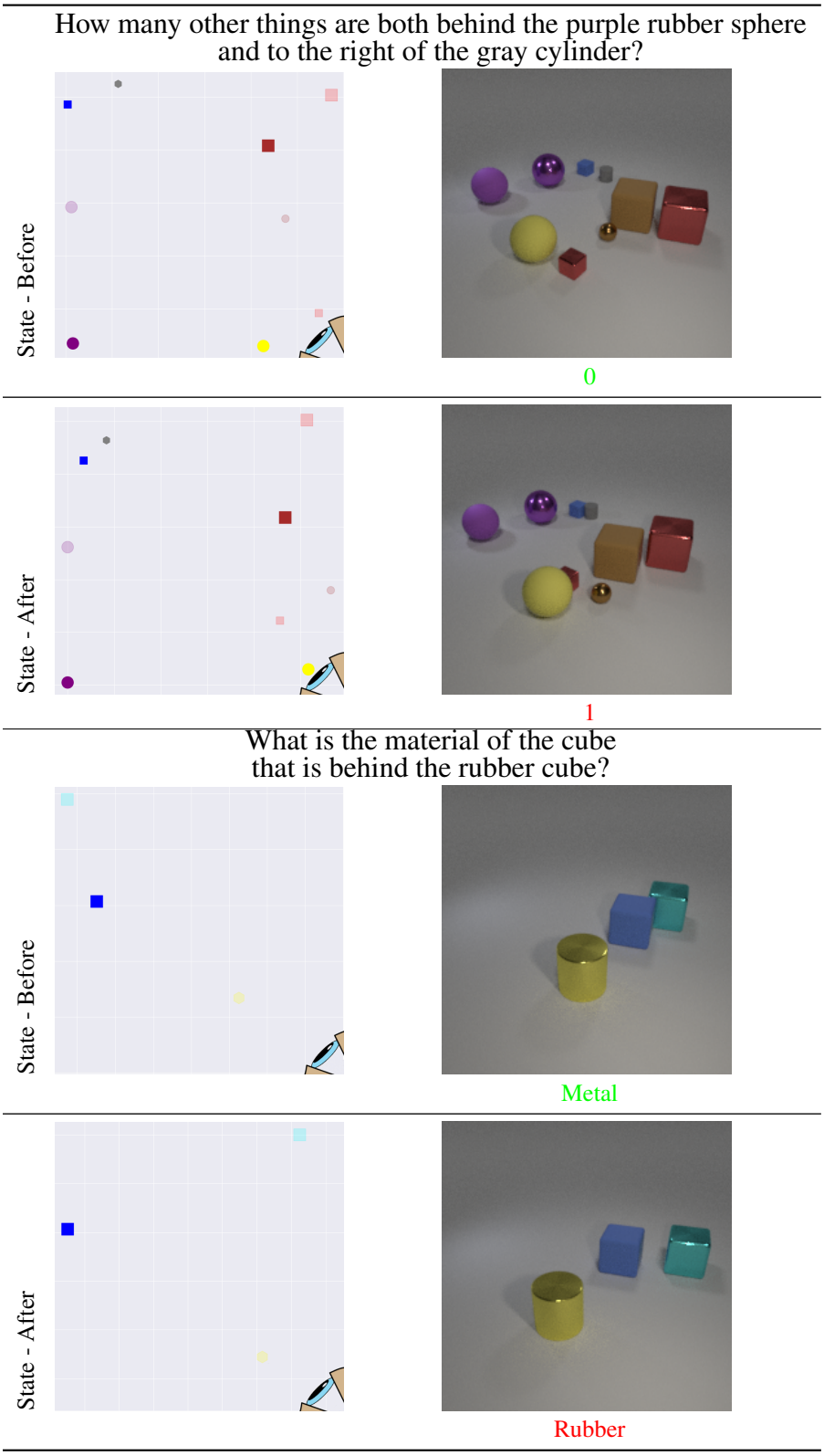


Figure 8: Qualitative results on *state-input Visual-QA Player*. For each example, a top-down view of the scene is presented. The eye at the bottom right of each view represents the rendering camera. It corresponds to the *Visual-QA Player*'s viewpoint. Each scene is also rendered and presented side-by-side for comparison.

A.5 ALGORITHMS

We show pseudo-algorithms that we use to (Algorithm 1) calculate rewards, (Algorithm 2) train *Adversarial Player*, (Algorithm 3) play a game, (Algorithm 4) create a defence mechanism.

Algorithm 1 Calculate Rewards

new_answer : Answer produced by Visual Agent on perturbed image
old_answer : Answer produced by Visual Agent on original image
gt_answer : Ground Truth Answer
dr : Drop Reward
cr : Consistency Reward
fr : Fail Reward
$reward \leftarrow 0$
if $new_answer \neq old_answer$ **then**
    if $old_answer \neq gt_answer$ **then**
        $reward = reward + cr$
    else
        $reward = reward + dr$
    end if
else
    $reward = reward + fr$
end if
return $reward$

Algorithm 2 Training Pipeline

M : Minigames
Va : Visual Agent, Fe : Feature Extractor
A : Actor, C : Critic
Qre : Question Relevance Enforcer, Sce : Scene Constraint Enforcer
for $batch\ in\ M$ **do**
    $rewards, state_values, logprobs \leftarrow DataGame(M, Va, Fe, A, C, Qre, Sce)$
    $n \leftarrow |rewards|$
    $advantage \leftarrow rewards - state_values$
    $ploss \leftarrow -logprobs \times advantage$
    $vloss \leftarrow (state_values - stop_grad(rewards))^2/n$
    $loss \leftarrow ploss + vloss$
    $backprop(loss, A, C)$
end for
return

Algorithm 3 Game between players (Game)

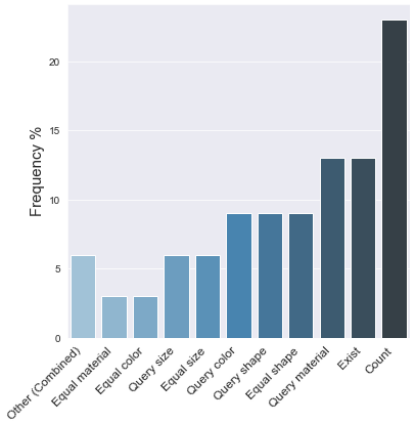
M : *Mini-game*
$\mathcal{P}_{\text{VQA}}$: Visual Agent, $\mathcal{S}_k$: Multi-modal Backbone
A : Actor, C : Critic
Qre : Question Relevance Enforcer, Sce : Scene Constraint Enforcer
isr : Invalid Scene Reward
for $batch\ in\ M$ **do**
  $rewards \leftarrow \{\}$
  $state_values \leftarrow \{\}$
  $logprobs \leftarrow \{\}$
  for $(image, scene, question, program, gt_answer)\ in\ batch$ **do**
    $old_answer \leftarrow \mathcal{P}_{\text{VQA}}(image, question)$
    $extracted_features \leftarrow \mathcal{S}_k(scene, question)$
    $dx_probs, dy_probs \leftarrow A(extracted_features)$
    $CatX \leftarrow Categorical(dx_probs)$
    $CatY \leftarrow Categorical(dy_probs)$
    $state_value \leftarrow C(extracted_features)$
    $dx \leftarrow$ sample $CatX$
    $dy \leftarrow$ sample $CatY$
    $new_scene \leftarrow Perturbate(scene, dx, dy)$
    $check_scene \leftarrow Sce(new_scene)$
    $check_question \leftarrow Qre(new_scene, program, gt_answer)$
    if $check_scene \wedge check_question = True$ **then**
      $new_image \leftarrow Render(new_scene)$
      $new_answer \leftarrow \mathcal{P}_{\text{VQA}}(new_image, question)$
      $rewards \leftarrow rewards \,||\, CalcRewards(new_answer, old_answer, gt_answer)$
    else
      $rewards \leftarrow rewards \,||\, isr$
    end if
    $state_values \leftarrow state_values \,||\, state_value$
    $logprob \leftarrow logprob || \, log(p(dx|CatX))) + log(p(dy|CatY)))$
  end for
end for
return $rewards, state_values, logprobs$

Algorithm 4 Defense Pipeline

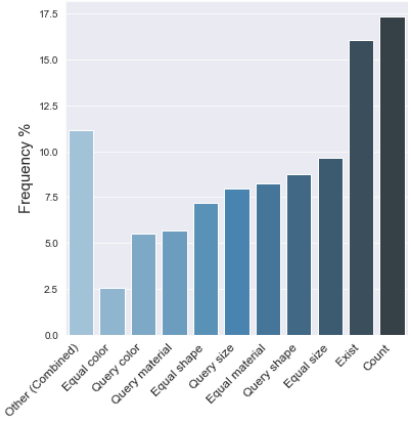
```
N : Defense Rounds
Va : Visual Agent
Agent_finetune : Pretrained RL Agent to fintune Va against
M_finetune : Minigame Training set of Agent_finetune
Agent_eval : Pretrained RL Agent to be used as evaluator
M_eval : Minigame Evaluation set of Agent_eval
MixExamples : Whether to use original samples from CLEVR
for epoch in N do
    batch_solved = 0
    for batch in M_finetune do
        for (image, scene, question, program, gt_answer) in batch do
            predictions ← {}
            correct ← {}
            new_image ← Agent_finetune(scene, question)
            if MixExamples = True then
                predictions ← predictions || Va(image, question)
                correct ← correct || gt_answer
            end if
            predictions ← predictions || Va(new_image, question)
            correct ← correct || gt_answer
            loss = CrossEntropy(predictions, correct)
            batch_solved+ = Accuracy(predictions, correct)
            backprop(loss, Va)
        end for
    end for
    if batch_solved/len(M_finetune) = 100 then
        break
    end if
end for
return Va
```

A.6 SENSITIVITY TO QUESTION TYPES

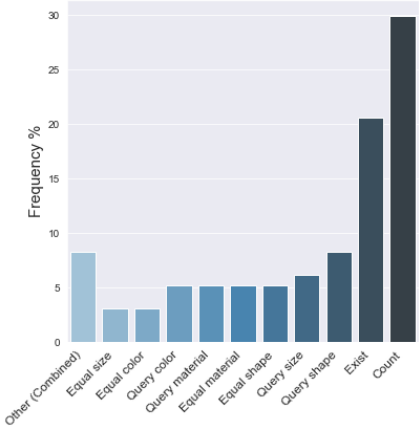
Figure 9 shows the susceptibility of CLEVR models to scene manipulations of *Adversarial Player*. We observe that especially *counting* and *existence* questions are the 'back-doors' for our scene manipulations. Questions of those two types typically involves multiple steps of reasoning. *Adversarial Player*'s scene manipulations make them more likely that reasoning will fail at some stage.



(a) FiLM



(b) TbD



(c) Mdetr

Figure 9: Histograms of the model's susceptibility to scene manipulations conditioned on a question type.

A.7 CONVERGENCE

Figure 10 shows convergence plots of *Adversarial Player* during training against FiLM, TbD and MDetr. We use different initialization seeds and 30 trials. *Adversarial Player* is trained either from *states* or *pixels*. The former yields higher performance and sometimes better convergence. We use the *Drop* metric that measures the accuracy drop after the *Visual-QA Player* is manipulated. The higher *Drop*, the more successful manipulations are.

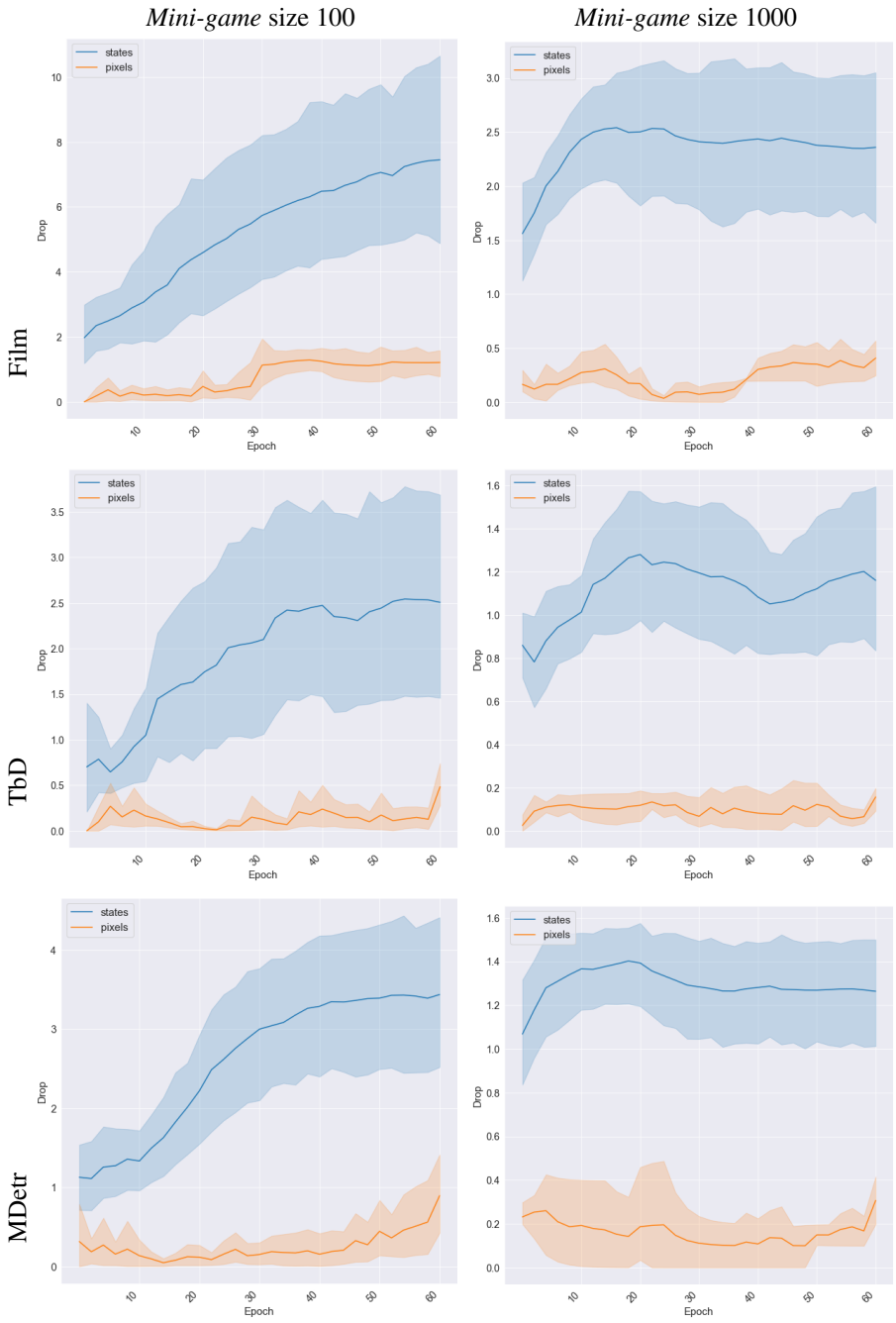


Figure 10: Performance of *Adversarial Player* for different training snapshots. We show the mean and variance over thirty trials. *Adversarial Player* is either trained from *states* (blue) or *pixels* (orange).

A.8 PERFORMANCE DISTRIBUTION PLOTS

Figures 11 and 12 show the distribution of the *Adversarial Player* performance, where we show how often (y-axis) the given *Drop* score is achieved (x-axis). The *Drop* metric measures the accuracy drop after the *Visual-QA Player* is manipulated. The higher *Drop*, the more successful manipulations are. Larger *Mini-games* lead to more consistent (narrower distributions) but lower performance. This behaviour suggests that scene diversity present in larger *Mini-games* lead to more stable scene manipulations. However, they do so at the cost of increasing the complexity of the optimization problem.

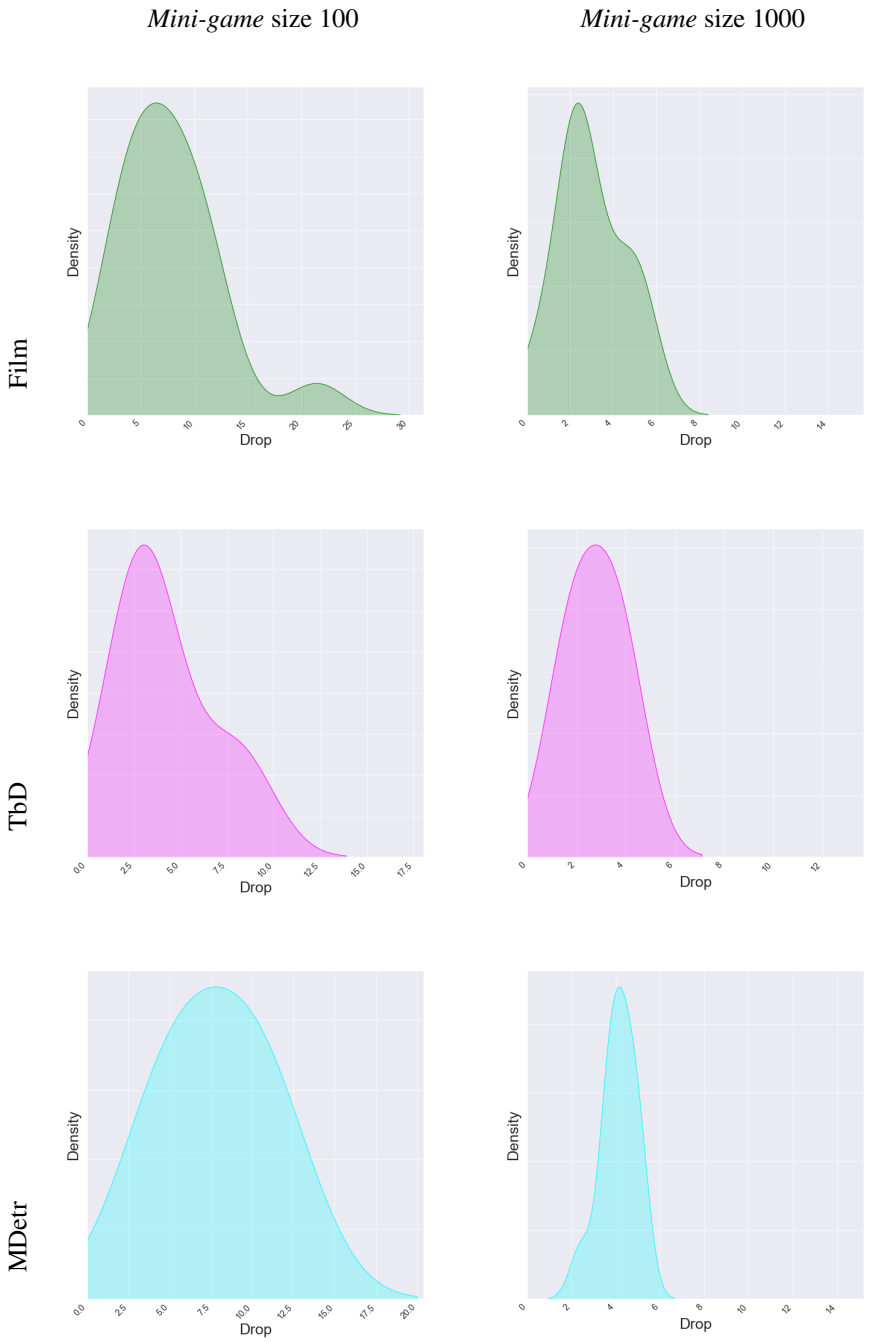


Figure 11: *Mini-games* performance distribution for *state-input Adversarial Player*.

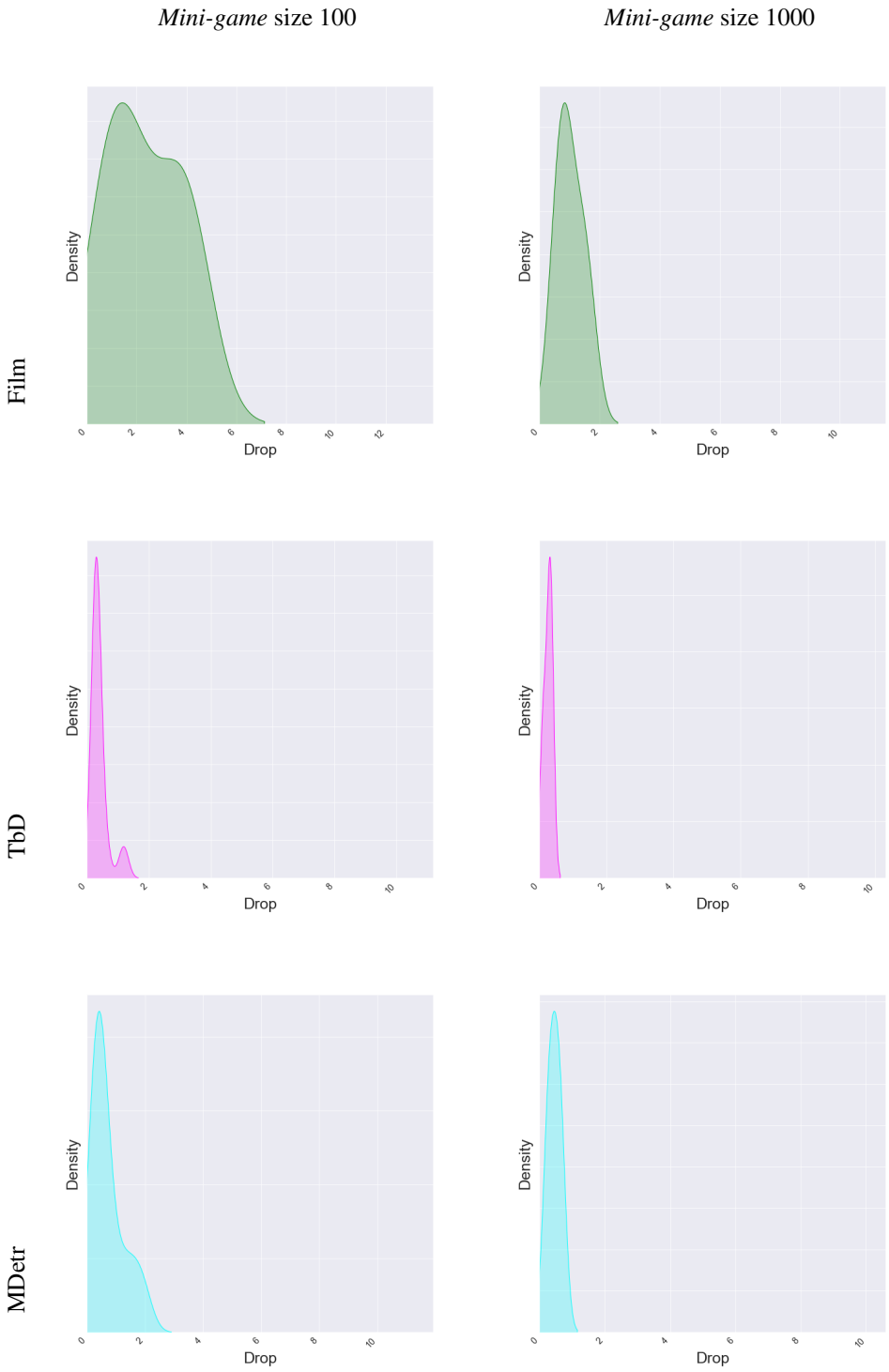


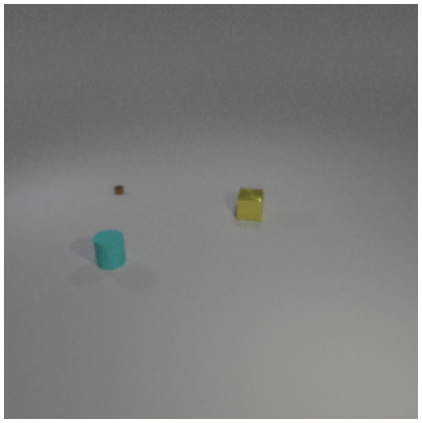
Figure 12: *Mini-games* performance distribution for *pixel-input Adversarial Player*.

A.9 OUT-OF-DISTRIBUTION MANIPULATIONS

If we do not provide extra constraints on the scene generation process with our environment enforcers, *Adversarial Player* may find an easy manipulation that changes the camera pose or location, effectively 'zooming out' the whole scene. It does so by stretching all the object coordinates in the scene. Figure 13 illustrates that. For instance, *large* objects look much smaller than typical examples. As such constructed scenes are quite different from the ones that *Visual-QA Player* has observed during training, we categorize such manipulations to be *out-of-distribution*. Note that, due to our *in-distribution* environment enforcers, such scenes are prohibited in our pipeline.

(a) Shape of the blue cube is misclassified as sphere.

(b) Large, brown cylinder is misclassified as small.



(c) Large, yellow cube is misclassified as small.

Figure 13: Out-of-distribution examples.

A.10 ADDITIONAL QUALITATIVE RESULTS

In Figures 14-23, we provide more qualitative results.

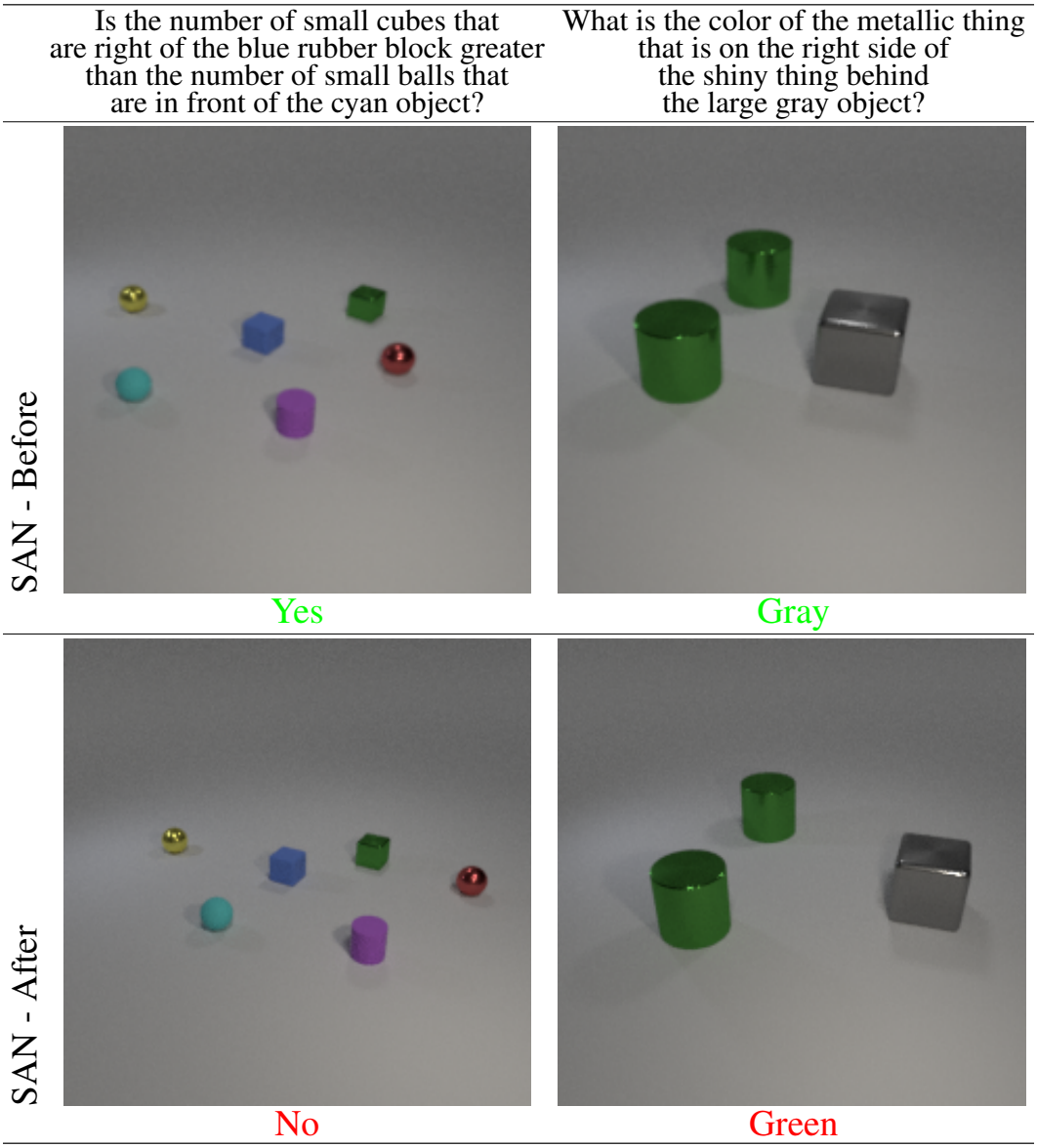


Figure 14: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

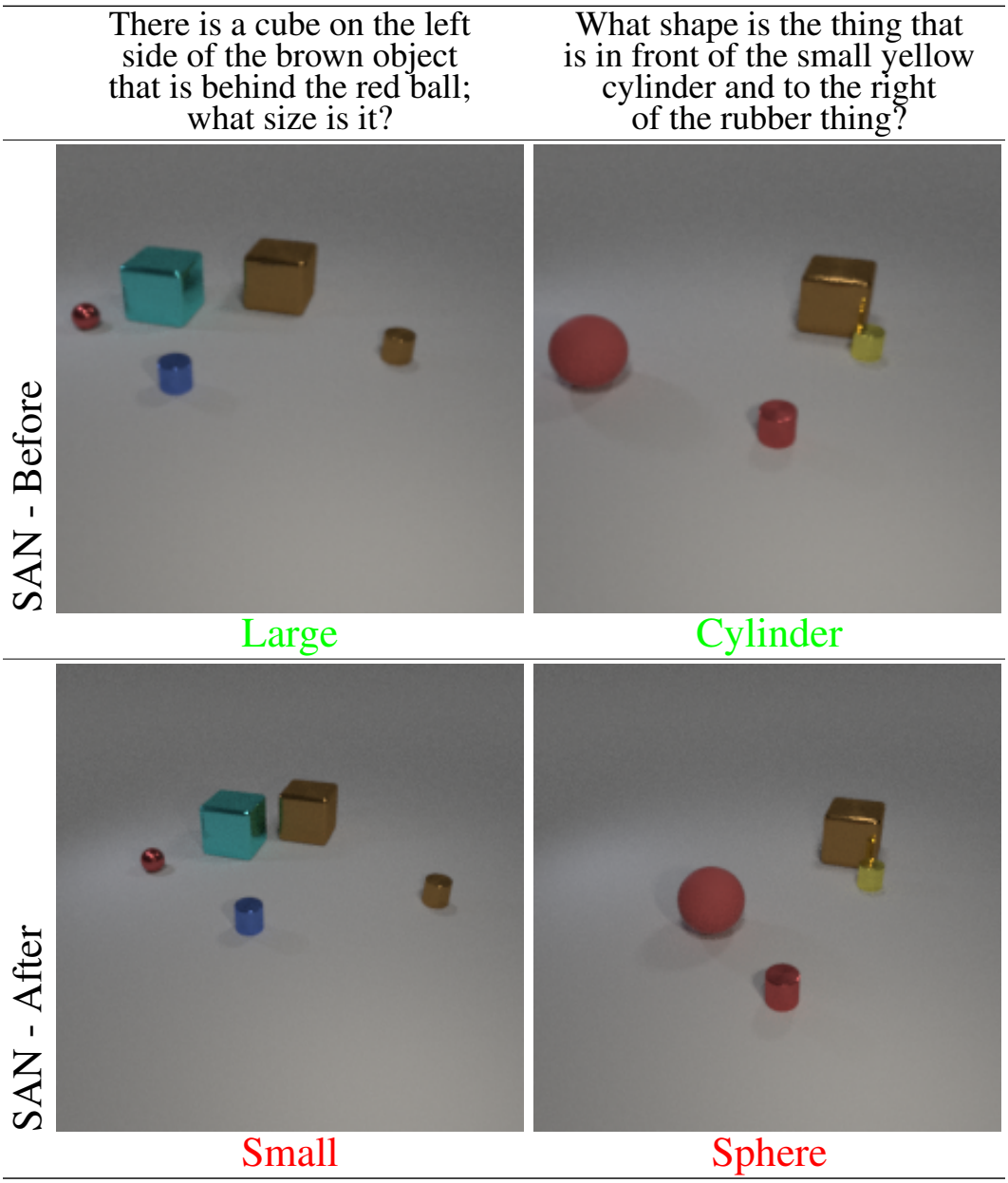


Figure 15: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

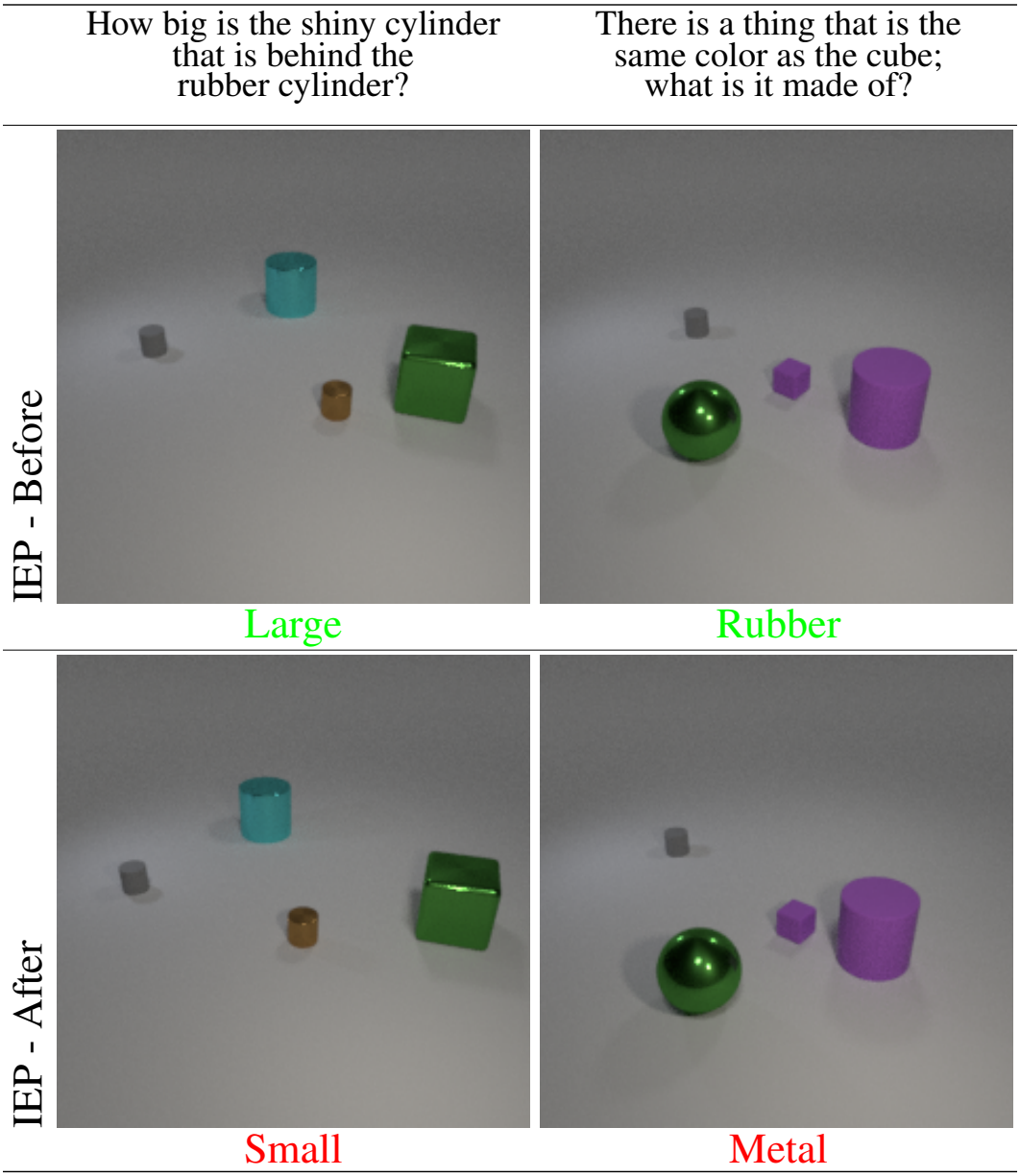


Figure 16: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

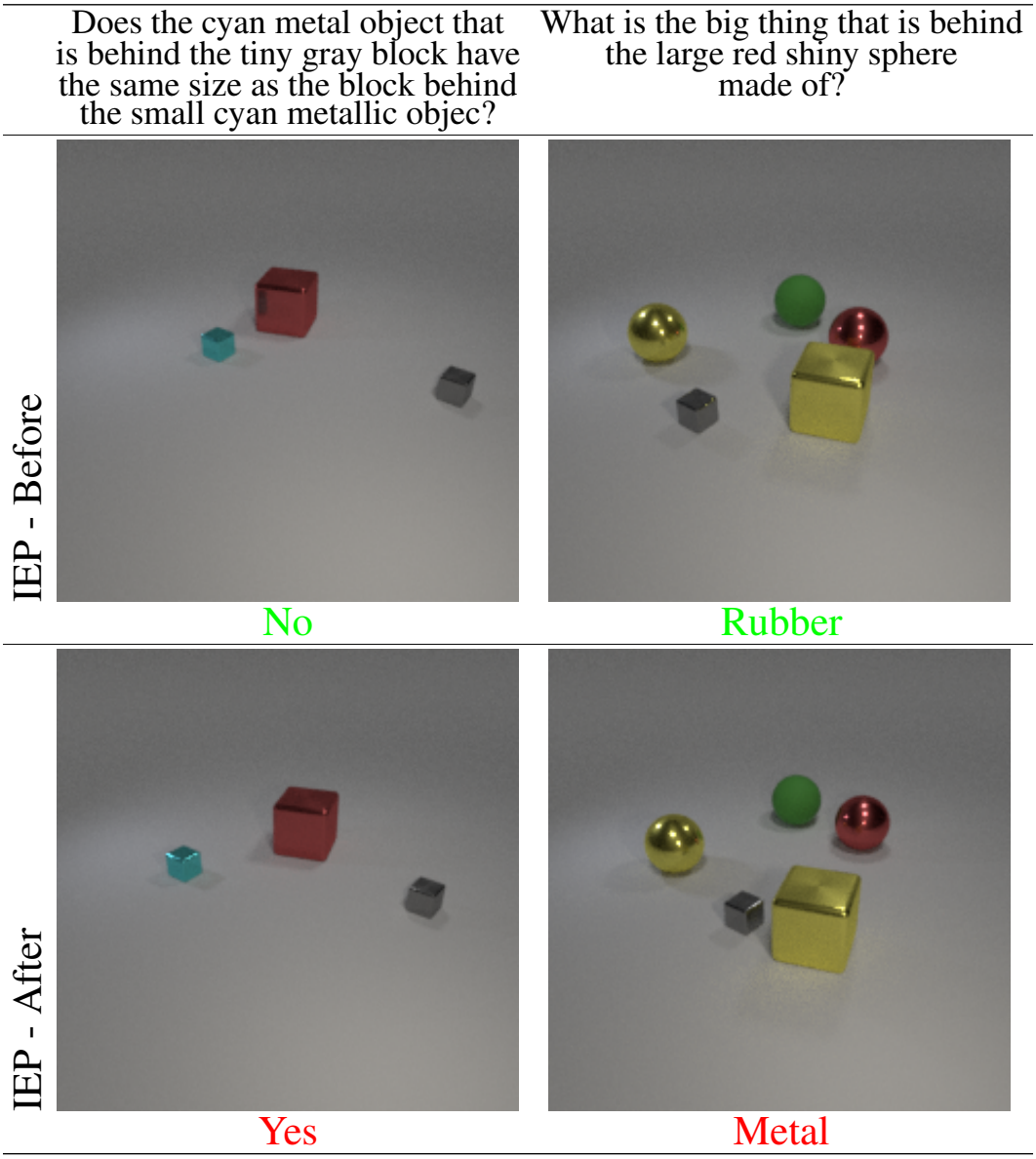


Figure 17: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

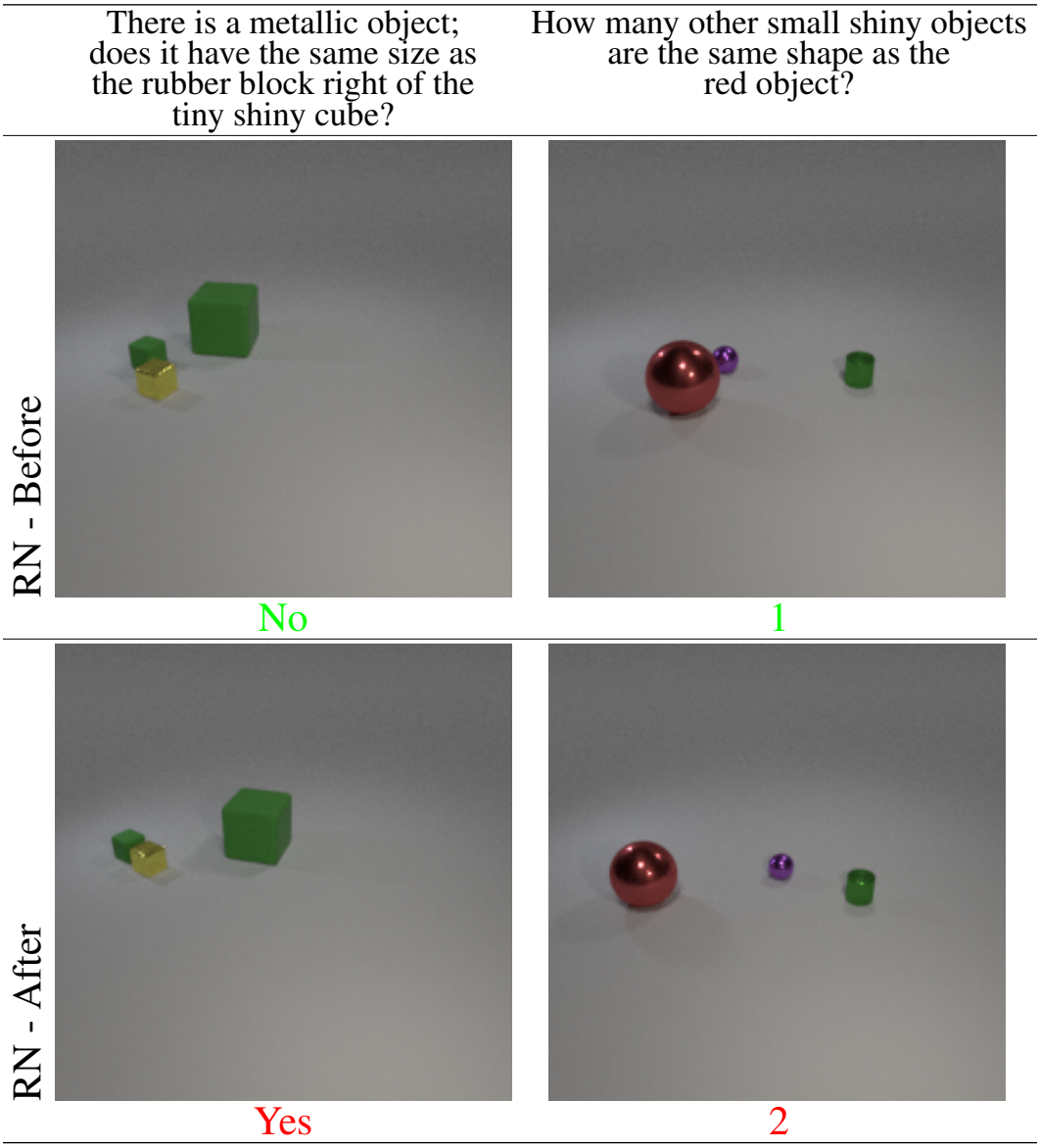


Figure 18: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

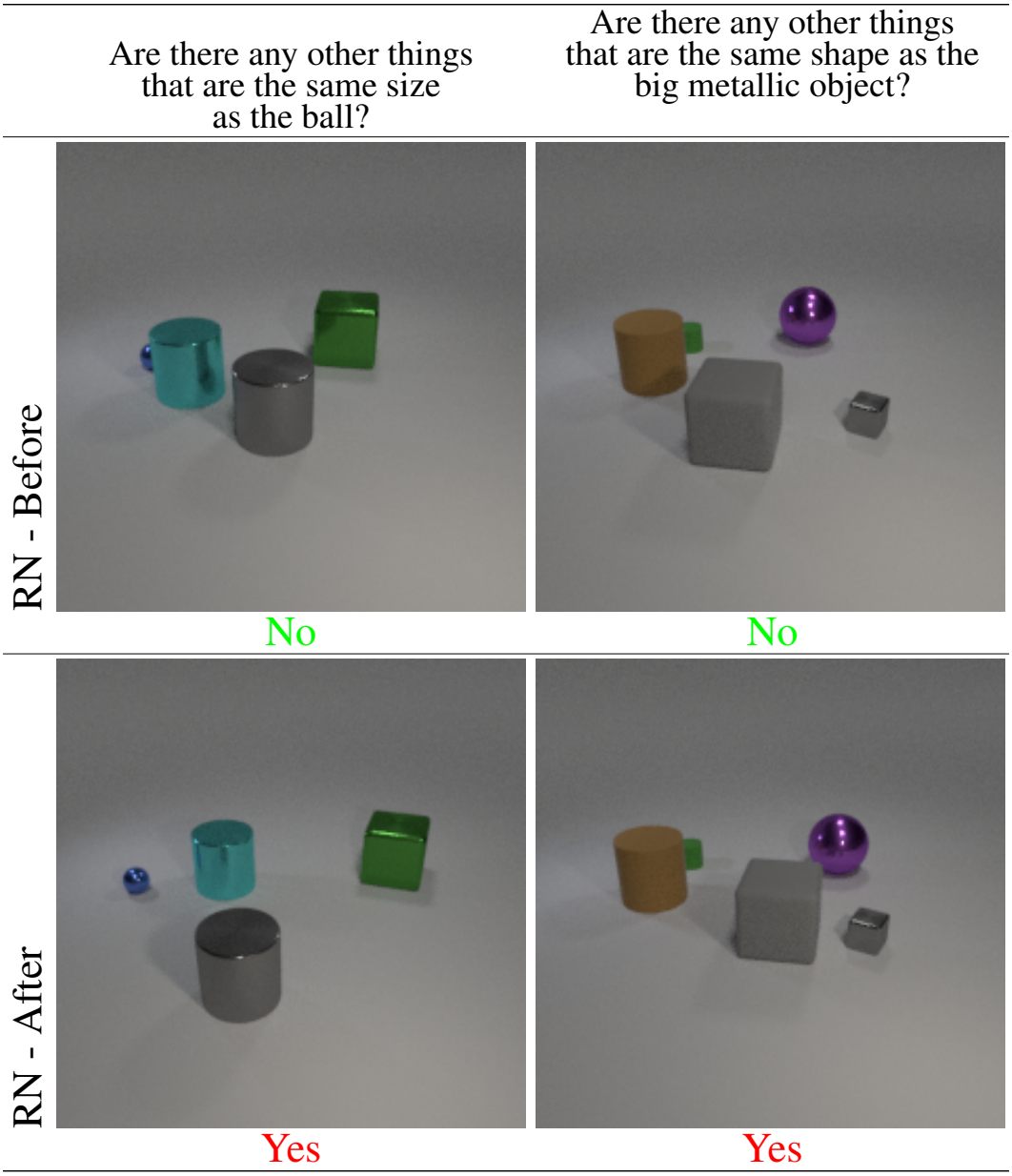


Figure 19: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

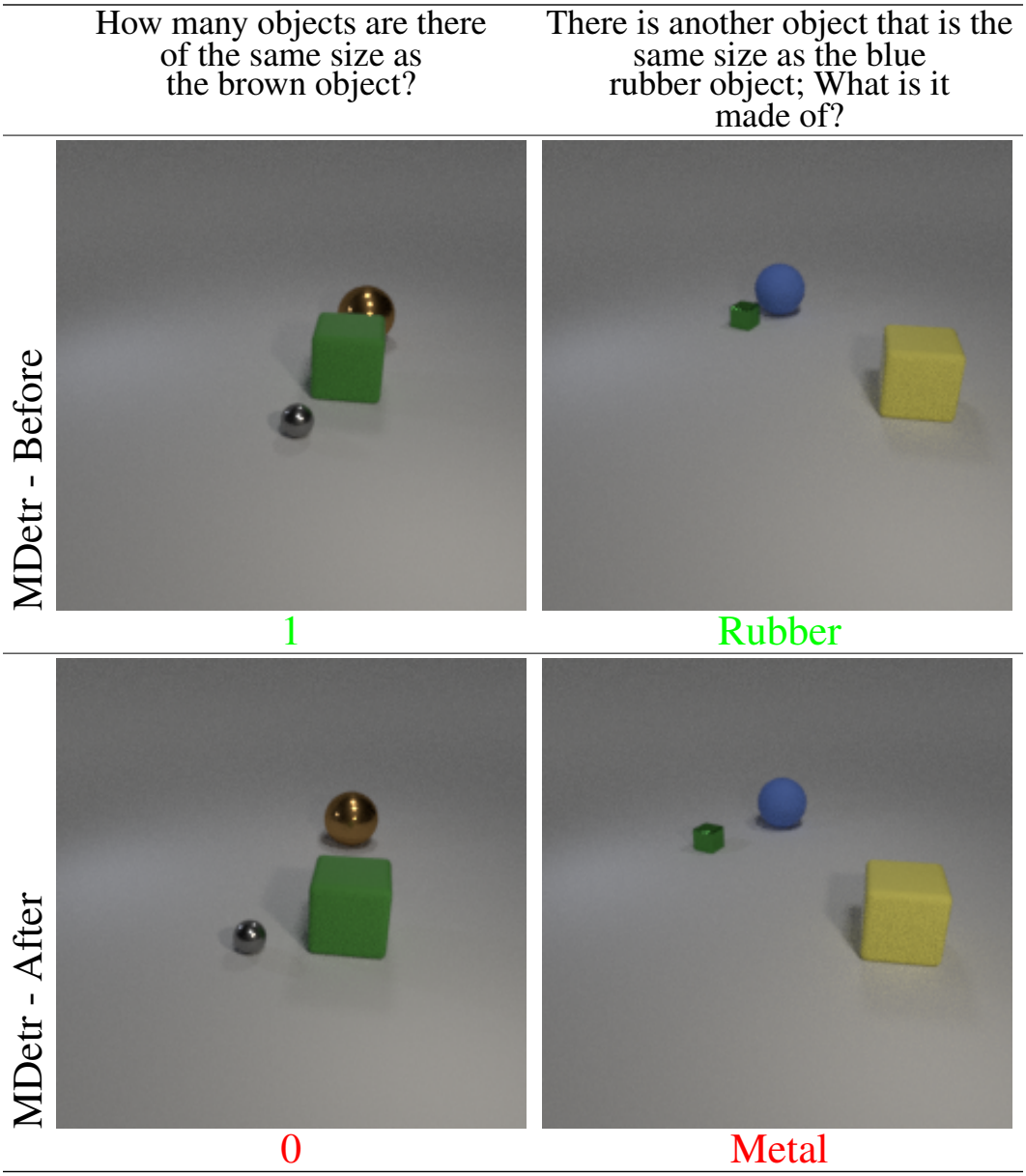


Figure 20: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

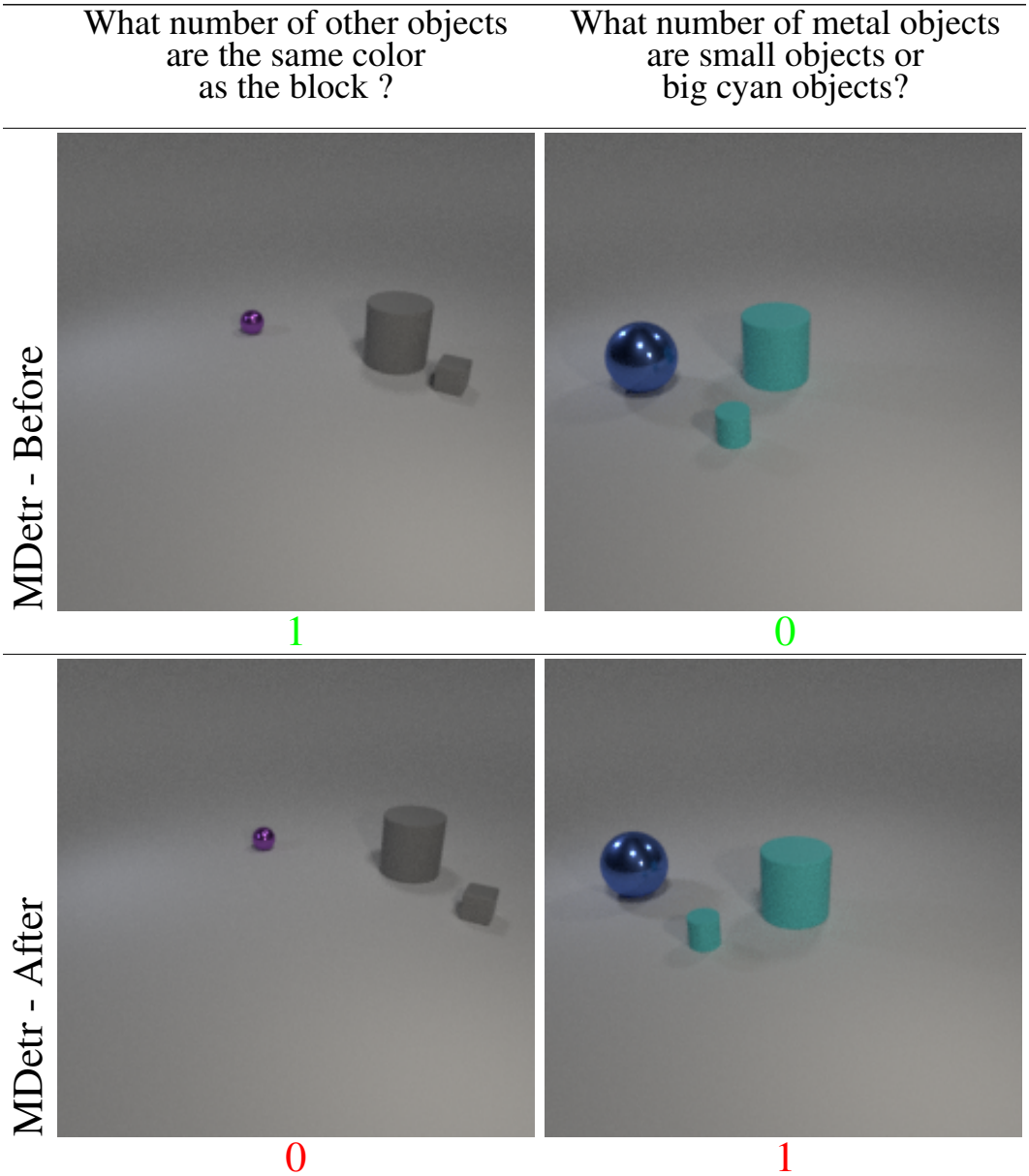


Figure 21: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

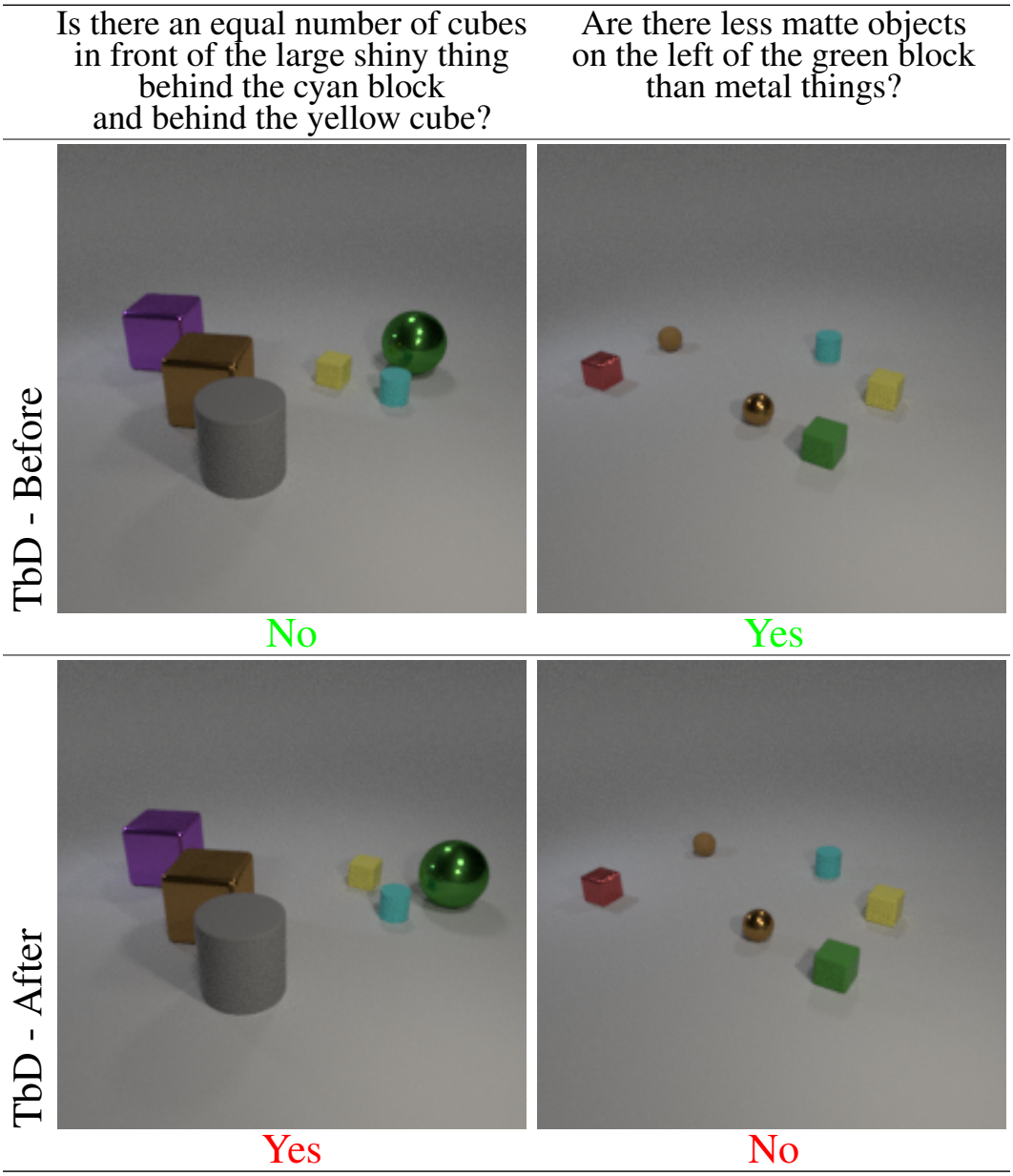


Figure 22: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

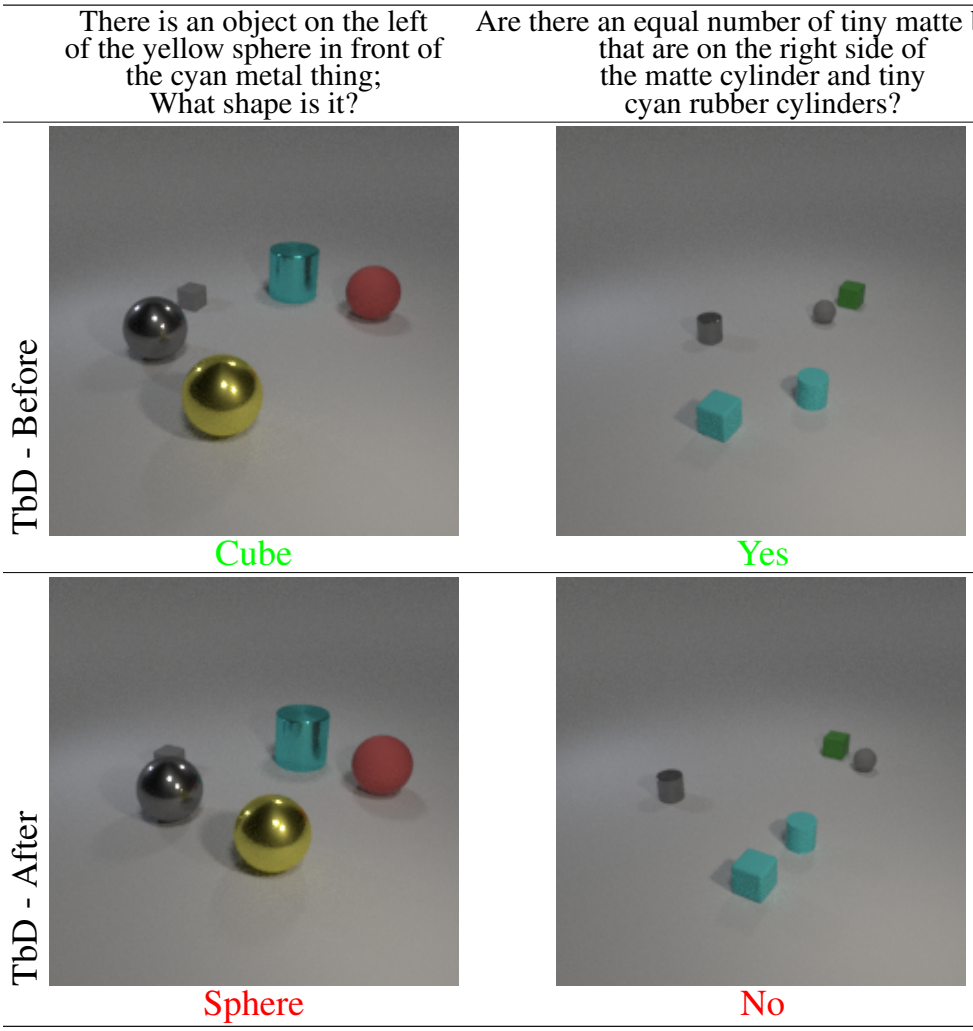


Figure 23: Manipulations of CLEVR models. We show results *before* and *after* scene manipulations.

A.11 QUANTITATIVE RESULTS WITH p-VALUES

We extend the quantitative results of the main paper by also reporting p-values of the one-sample hypothesis testing. Here, we also use the *Accuracy Drop* metric that measures the accuracy drop after the *Visual-QA Player* is manipulated, and the *Consistency Drop* that measures how many times the manipulated *Visual-QA Player* changes its answer, independently if that is a correct or wrong answer. The higher *Drop Accuracy* or *Consistency Drop*, the more successful manipulations are. Note that we use the same metrics as rewards to our *Adversarial Player*. We use T-Test (Helmert, 1876; Lüroth, 1876) for each metric all the runs. Our null hypothesis is that the population mean of all the games is zero, indicating that a manipulation is unsuccessful, and the results of our *Adversarial Players* are extreme cases of a good performance, i.e, $H_0 : \mu_l = 0, l \in [\text{Drop}, \text{Consistency}]$. As an alternative hypothesis, we assume that the population mean is greater than zero, i.e., $H_A : \mu_l > 0, l \in [\text{Drop}, \text{Consistency}]$. The same setup stands for both the *Consistency* and the *Drop* metric. Tables 4 and 5 show the full table with p-values computed. Note that only in two cases, *Adversarial Player* does not manipulate the scene convincingly (TbD and Mdetr for the *pixel-input Adversarial Player*).

Table 4: Results of the game with the *state-input Adversarial Player*.

Model	*Mini-game* size	Average		Maximum		p-value	
		Consistency Drop %	Accuracy Drop %	Consistency Drop %	Accuracy Drop %	Consistency Drop	Accuracy Drop
SAN	10	-23.9	-14.2	-60.0	-60.0	0.000	0.000
	100	-10.7	-8.3	-34.1	-33.9	0.000	0.000
	1000	-3.5	-2.5	-8.0	-5.1	0.001	0.000
FiLM	10	-14.8	-12.7	-50.0	-50.0	0.003	0.006
	100	-7.8	-7.3	-22.3	-21.4	0.000	0.000
	1000	-3.1	-2.4	-5.7	-5.6	0.000	0.000
RN	10	-20.9	-13.6	-50.0	-50.0	0.000	0.000
	100	-10.5	-8.2	-32.1	-32.1	0.000	0.000
	1000	-3.3	-2.8	-4.1	-3.4	0.000	0.000
IEP	10	-13.9	-13.0	-50.0	-50.0	0.001	0.003
	100	-6.9	-6.8	-23.2	-23.2	0.000	0.000
	1000	-2.9	-2.8	-3.2	-3.0	0.000	0.000
TbD	10	-5.3	-5.1	-40.0	-40.0	0.011	0.012
	100	3.8	-2.5	-8.0	-8.0	0.000	0.000
	1000	-1.1	-1.1	-3.6	-3.6	0.000	0.000
Mdetr	10	-6.6	-6.0	-40.0	-40.0	0.018	0.021
	100	-4.9	-3.6	-14.2	-13.3	0.000	0.000
	1000	-1.3	-1.2	-5.4	-5.2	0.000	0.000
State Input Model	10	-8.5	-7.7	-20.0	-20.0	0.020	0.034
	100	-2.3	-2.1	-5.1	-4.3	0.000	0.000
	1000	-1.2	-1.1	- 1.7	-1.7	0.000	0.000

Table 5: Results of the game with the *pixel-input Adversarial Player*.

Model	*Mini-game* size	Average Consistency Drop %	Average Accuracy Drop %	Maximum Consistency Drop %	Maximum Accuracy Drop %	p-value Consistency Drop	p-value Accuracy Drop
SAN	10	-12.8	-11.4	-40.0	-40.0	0.008	0.018
	100	-6.4	-3.9	-13.3	-8.0	0.000	0.001
	1000	-2.3	-1.4	-3.4	-1.7	0.000	0.000
FiLM	10	-3.62	-2.6	-10.0	-10.0	0.056	0.154
	100	-1.7	-1.4	-4.4	-3.9	0.000	0.000
	1000	-0.6	-0.4	-1.6	-1.5	0.000	0.000
RN	10	-9.4	-7.2	-30.0	-20.0	0.021	0.065
	100	-3.2	-2.5	-9.8	-6.2	0.000	0.000
	1000	-2.3	-1.7	-2.8	-2.3	0.000	0.000
IEP	10	-2.9	-2.5	-10.0	-10.0	0.111	0.171
	100	-1.5	-1.3	-3.5	-3.5	0.001	0.004
	1000	-0.4	-0.3	-1.3	-1.2	0.000	0.000
TbD	10	0.0	0.0	0.0	0.0	1.000	1.000
	100	-0.6	-0.4	-1.2	-1.1	0.017	0.078
	1000	-0.2	-0.1	-0.3	-0.3	0.000	0.000
Mdetr	10	0.0	0.0	0.0	0.0	1.000	1.000
	100	-1.2	-1.1	-2.0	-1.9	0.002	0.003
	1000	-0.4	-0.3	-0.9	-0.6	0.000	0.000
State Input Model	10	-0.9	-0.8	-5.0	-5.0	0.033	0.038
	100	-0.7	-0.7	-1.8	-1.8	0.031	0.031
	1000	-0.3	-0.3	-1.0	-1.0	0.000	0.000