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# Motion-induced overestimation of the number of items in a display

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Abstract. Subjects were asked to report the number of items in a display as the items moved along a circular path around the fixation point. As the rotation speed increased, the apparent number of items also increased. This motion-induced overestimation (MIO) effect was investigated in three experiments. In the first experiment, the effect of rotation speed and set size was explored with an enumeration task. The overestimation error increased with an increase in speed or number of items in the display. In the second experiment, we used an adjustment paradigm to measure the speed threshold of MIO effect onset. Temporal rate of the display, which was defined as product of rotation speed and the number of rotating items, was the determining factor of MIO onset. In the third experiment, moving items were marked with different colours. Surprisingly, the number of perceived items was still overestimated even though the number of perceived colours was not.

## 1 Introduction

Standing for a few minutes in a street, we witness a world that is abundant with 'moving' objects: people running or walking, wheels rolling, leaves falling, birds flying. Our ability to individuate and count objects in such natural settings is critical for our everyday activities. Since few of these objects stand still for us to count them, it is important to examine whether the motion of the objects affects our ability to estimate their number.

As an example, if you look at the wheel bolts of a car driving off when the traffic light turns green and try to count the bolts, you may sense that the number of bolts increases as the car accelerates! A wheel with four bolts may appear to have five at moderate speeds, then perhaps six, before finally only an indivisible blur is seen. Here, we investigate the effect of speed on judged numerosity and we find that movement indeed induces an overestimation. We have named this supernumerary effect "motion-induced overestimation" (MIO).

This effect has been reported previously by Purves et al (1996) while working on the 'wagon wheel illusion'. They briefly mentioned the overcounting of rotating spokes in continuous light but did not explore it further. The aim here is to introduce MIO in more detail and to investigate the most influential variables that affect this phenomenon. MIO is a robust illusion and everybody can easily experience it by looking at various rotating devices (like bolt pattern of car wheels) under continuous light. Like other visual illusions, MIO gives us a particular opportunity to study the behaviour of the naturally developed visual system under special conditions. This could help us investigate the way our visual system enumerates moving objects.

Previous studies on counting and numerosity estimation have mainly focused on the number of items (Trick and Pylyshyn 1994), stimulus duration (Alam et al 1986), spatial and temporal configuration of dynamic items (Allik and Tuulmets 1991, 1993; Ginsburg 1978, 1991; Van Oeffelen and Vos 1982), homogeneity of items (Frick 1987), orientation and colour (Atkinson et al 1976), size (Allik et al 1991; Ginsburg and Nicholls 1988) and other effects that could influence counting ability in static scenes. There are only few studies on counting of smoothly moving objects; however, in our daily experience we encounter these kinds of objects frequently

We have measured some parameters that influence the occurrence of MIO. Our stimuli consisted of a variable number of visual items moving in a circular trajectory around a fixation point. Three experiments were conducted. In the first experiment, we established the presence of MIO for various numbers of items and speeds in a simple enumeration task. In the second experiment, the method of adjustment was used to measure the threshold speed required to obtain the overestimation effect for displays with 3 to 6 items. In the third experiment, rotating items were marked with different colours and although the perceived number of items was still overestimated, the perceived number of colours was not.

## 2 Experiment 1

This experiment was designed to measure the effect of speed on the estimated number of items in a moving display. Displays were presented at different speeds for unlimited time and subjects were asked to report the number of items in the display.

### 2.1 Methods

All experiments ran on a Pentium IV (1.8 GHz) PC. Stimuli were displayed on a CRT monitor (710A Hansol, 17 inches),  $800 \times 600$  pixel resolution at 100 Hz frame rate.

The stimuli (figure 1) moved in a circular path with a diameter of 3.6 deg of visual angle (from a 57 cm viewing distance). The number of items varied randomly from 3 to 6 from trial to trial. Each item was an arc, a section of an annulus centred at the fixation, with a radial width of 0.56 deg, extending along a sixth of the circumference of the circular rotation path when there were 3 items, an eighth when there were 4, a tenth for 5, and a twelfth for 6 items. We chose these item sizes so that the overall luminance did not vary with the number of items in the display and, therefore, gave no clue about the overall number of items. Arcs were distributed evenly on the circular path. They rotated together in the clockwise direction around the fixation point located in the centre of the display. The rotation speed varied randomly from trial to trial so that all speeds were tested the same number of times at all display sizes. The speeds were as follows: 0.83, 0.91, 1.00, 1.11, 1.25, 1.43, 1.67, and 2.00 rotations per second (Hz). Subjects viewed the display binocularly from a distance of 50 to 60 cm.



Figure 1. One frame of a display with four items. The four light-gray arcs rotate around the central fixation point on a dark-gray background.

Thirteen naïve subjects with normal or corrected-to-normal vision participated voluntarily in the experiment. Each subject completed two experimental blocks with 160 trials. A block contained 5 trials for any combination of above-mentioned speed levels and item numbers. Subjects were not aware of the possible number of items in each trial and also were not told the maximum or minimum item numbers. They were asked to report the number of perceived moving items while fixating on the fixation point. A trial was started after subjects pressed 'enter' on a computer keyboard and lasted until subjects responded by pressing a number on the keyboard. When subjects were unable to estimate the number of rotating arcs, they pressed the 'space' key. Intertrial intervals were therefore determined by subjects. Sessions lasted on average 40 min.

## 2.2 Results and discussion

The average reported number of items in the display is plotted in figure 2 as a function of rotation speed for one of the subjects and the subject population. Both graphs show that, when rotation speed rises, the reported number of items increases for all display sizes except 3. Conditions for which subjects were unable to make an estimation in more than 50% of trials ('space' key responses) were excluded. Figure 3 shows the same result as a function of entry flicker rate (rotation speed × number of items) separately for each display size for the subject population.



Figure 2. Average reported item numbers in experiment 1 as a function of rotation speed separately for each display size. (a) Data of one of the subjects, SFR. (b) Average data for all subjects. Conditions in which subjects were not able to count the items in more than 50% of trials are excluded. Error bars represent  $\pm 1.0$  SEM.



Figure 3. Average reported number of items by all subjects as a function of entry flicker rate (rotation speed  $\times$  number of items) shown separately for each display size. Error bars represent  $\pm 1.0$  SEM.

The numerosity error was calculated as the difference between the reported and actual number of items for each trial. A two-way ANOVA was performed on these differences to investigate the effect of the rotation speed and the number of items on the amount of overcounting error. The 'space' key hit trials were excluded from the analysis. After pooling the data from all subjects, the ANOVA analysis showed a significant effect of both rotation speed ( $F_{7,3481} = 60.5$ ,  $p < 10^{-4}$ ) and actual number of items ( $F_{3,3481} = 111.3$ ,  $p < 10^{-4}$ ) on the overcounting error. However, the interaction of speed and the number of items was also significant ( $F_{21,3481} = 16.6$ ,  $p < 10^{-4}$ ), reflecting the lack of effect of speed for display size 3, shifting to an increasing effect throughout the range of tested speeds for display size 6. Visual inspection of these plots suggests that as the number of items in the display increases, overestimation begins to occur at lower and lower speeds. In experiment 2 this possibility was examined more directly.

Further analysis on the data of individual subjects demonstrated a significant main effect of speed and number of items in the majority of subjects. In 12 of 13 subjects there was a significant effect of speed on the amount of overcounting ( $p < 10^{-3}$ ), and in 11 of 13 subjects, the actual number of items had a significant effect on the extent of overcounting error ( $p < 10^{-3}$ ). Interaction of speed and number of items was significant in 12 subjects ( $p < 10^{-3}$ ).

Figure 4 shows the average incidence of space-key hits in experiment 1. It shows that estimating the number of rotating items becomes more difficult at higher speeds and with a higher actual number of items. A possible problem with more space-key hits at higher speeds and numbers of items is that it could conceal the likelihood of the illusion in situations where subjects were uncertain about their estimate of display size with the number of perceived items being too great to be counted (a fact frequently mentioned by subjects).



Figure 4. Average incidence of space-key hits in experiment 1 for various item numbers and rotation speeds.

Our aim in experiment 1 was to ascertain the existence of a systematic overestimation error for moving visual items. We preferred to use the data points in which subjects were more certain about the accuracy of their responses. Thus, instead of a forced-choice paradigm, we allowed our subjects to avoid reporting a number by pressing the space key when they were not certain about the number of items, and we analysed only the data points where subjects hit the space key in less than 50% of trials. The cost was that at higher speeds subjects hit the space key more frequently having perceived too many items, and this decreased the 'sensitivity' of experiment 1 in the measurement of the strength of the illusion. On the other hand, as subjects were more certain about their responses (as compared with a forced-choice task), this paradigm provided a better 'accuracy' in exploring the existence of the illusion.

## 3 Experiment 2

Experiment 2 was designed to measure the thresholds of the MIO effect more directly. In this experiment, subjects were aware of the number of items in the display and adjusted the speed of rotation until they perceived that the number of items was increased.

## 3.1 Methods

The stimuli and apparatus were the same as experiment 1. Six subjects from experiment 1 participated in this experiment. The experiment consisted of four blocks, each containing 10 trials of a constant number of rotating arcs. The number of arcs in a block was pseudorandomly chosen from 3 to 6. Subjects were told the actual number of moving items in each block, and were instructed to adjust the rotation speed and find the lowest speed at which the apparent number of items became greater than the actual number. The rotation speed ranged from 0.5 to 2.0 rotations s<sup>-1</sup> (Hz). Each trial started at a random initial speed and subjects could change it gradually through the trial by pressing nine different number buttons on the keyboard each corresponding to a step size. The finest step size was 0.02 and the coarsest one was 0.20 Hz. The direction of speed change—increase or decrease—was chosen by pressing '+' or '-' buttons, respectively. The trial terminated when subjects reported the adjusted threshold by pressing the 'enter' button. If subjects did not perceive any increase in the number of items, even at high rotation speeds, they hit the 'delete' key to terminate the trial.

### 3.2 Results and discussion

The results of experiment 2 show that as the actual number of items increases, the onset of MIO occurs at lower rotation speeds (figure 5a). Unlike in experiment 1, most of the subjects reported the illusion of overcounting for 3 items and in all trials subjects were able to find the threshold of the MIO effect, with the exception of one subject who pressed the 'delete' key in all trials with 3 moving items (see section 3.1). A repeated-measures ANOVA, performed on the thresholds reported by the subject population, showed a significant effect of the actual number of items on the onset speed threshold of the MIO ( $F_{3,12} = 96.8$ ,  $p < 10^{-5}$ ). The same effect was seen in all subjects individually (one-way ANOVA,  $p < 10^{-5}$ ).



**Figure 5.** (a) Speed thresholds of MIO onset as a function of display size. The MIO effect occurs at lower rotation speeds for larger display sizes. Error bars represent  $\pm 1.0$  SEM. (b) The same data replotted in terms of entry flicker (product of rotation speed and number of items).

In figure 5b, the result is replotted in terms of temporal rate (the flicker rate at any given point as the items pass over that point, ie the product of the rotation speed and the number of moving items). The temporal rate of MIO onset is fairly constant for the range of tested item numbers.

The speeds at which subjects report an overestimation in this experiment are noticeably lower than the speeds at which the data of experiment 1 suggest an overestimation would occur. For example, if we assume that overestimation would be reliably reported when the estimated number of items is, on average, 0.5 greater than the actual number, then, according to data of experiment 1 overestimation should not be reported at any speed within the range tested for 3 items and should happen for 4 items only at a speed of about 1.7 Hz. However, the threshold speeds from experiment 2 are 1.7 Hz for 3 items and 1.3 Hz for 4 items. The most likely source for this difference is the existence of possible alternative strategies that could be utilised by subjects in experiment 1. In that experiment subjects were instructed to report the number of rotating items, and the aim of this experiment was to show the existence of the overestimation error objectively. Subjects could therefore take advantage of any cue that helped the estimation of display size. When the display size changes, item size, inter-item spacing, and stimulus area cannot all remain constant. In our stimulus design, in experiment 1, stimulus area and luminance were kept constant at the expense of subjects having the cue of item size to judge the number of items. Since different numbers of items were presented to the subject in the same block in experiment 1, subjects could compare item size and inter-item spacing through the block to improve the accuracy of estimation. Also, occasional blinks and small drifts from the fixation point could offer additional help in estimating the number of items by providing a snapshot of the scene that could be used to judge the display size without being confounded by the motion present in the scene. All of these cues facilitate estimation of the number of items and can increase the speed threshold of the MIO effect. Therefore, experiment 1 has not been accurate for measuring the threshold, although it provides objective evidence for the existence of the phenomenon. On the other hand, in experiment 2, subjects were aware of the number of items before the start of the trials and were instructed to report the subjective onset of MIO. They may, therefore, choose to ignore the above-mentioned cues of display because they already know that the display contains that number of items and instead, concentrate on reporting when overestimation becomes apparent.

## 4 Experiment 3

We have shown in the previous experiments that moving items could appear more numerous than they actually are. Here, we ask what happens to object attributes such as colour. If extra objects are perceived in a moving display, what colour do these extra items have? Does the number of perceived colours also increase? Or do such unique identifying features cancel the MIO effect?

## 4.1 Methods

With the exception of item colour, the stimuli and apparatus were the same as in the previous experiments. Five subjects from experiment 2 participated in this experiment. All displays were limited to 4 items and the arcs were painted by four different photometrically isoluminant colours: red, green, blue, and yellow. Two blocks of 20 trials were presented to the subjects. In the first block they were asked to adjust the rotation speed to the point where they perceived more than 4 moving items. In the second block subjects were to find the speed threshold at which they perceived more than 4 colours, ignoring the perceived number of items. The two blocks were otherwise identical. The adjustment procedure was the same as in experiment 2.

## 4.2 Results and discussion

In the first block, all subjects reported an increase in the number of coloured rotating items and adjusted the rotation speed to the threshold of seeing this increase. The average speed threshold of the MIO effect was  $1.80 \pm 0.10$  Hz (mean  $\pm$  SE). This is slightly higher than the threshold for 4 items in experiment 2 (mean  $\pm$  SE,  $1.32 \pm 0.10$ ) (*t*-test, p < 0.005). However, in the second block, none of the subjects reported perceiving more than 4 colours at any speed in the tested range. Also, no colour was repeated more than once as subjects reported. Since the maximum rotation speed in this experiment was 2 Hz (only slightly faster than the threshold speed in the first block), one could claim that the perception of a new colour may occur at higher speeds. Thus we repeated the second block, and let subjects increase the rotation speed up to 4 Hz. Subjects again perceived only four colours in the display even at these higher rotation speeds where moving items looked like shooting stars.

## 5 General discussion

Our results indicate that the perceived number of items in a dynamic scene may be greater than the actual number. Data from the first experiment show that, while subjects are able to accurately judge the number of items rotating at low speeds, they overestimate the number of items at higher speeds. In this experiment, subjects were unaware of the actual number of rotating items and they were allowed to use any possible cue to judge the number of items. Also, they were not forced to report a number and they could avoid reporting it when they were not able to count the objects. The presence of overestimation error even when subjects are free to use alternative estimation strategies and to avoid responding when they are not sure about their estimation, provides objective evidence for motion-induced overestimation effect.

Purves et al (1996) briefly documented the same phenomenon but attributed it to discrete or episodic information processing by our visual system, which, in continuous light, could emulate the illusion of supernumerary spokes under stroboscopic illumination. The main focus of their measurements was on the perception of reverse rotation (a characteristic of wagon-wheel illusion) under stroboscopic and continuous light (although see Pakarian and Yasami 2003). Unfortunately, Purves et al did not measure the gradual increase in perceived item number with speed (in continuous light). They just mentioned it as a difference between the results of continuous and stroboscopic illumination conditions. If our visual system did use discrete sampling of the incoming stream, as these authors claimed, the overestimation would be limited, as it is in strobe illumination, to integer multiples of the actual display numbers, a result that was not obtained from the data of our experiment 1.

Our experiment 2 was designed to estimate the threshold speed at which MIO onset becomes apparent for different numbers of items. In this experiment, the threshold is measured more accurately than in experiment 1 (see section 3.2). The results of this experiment indicate that the illusion of overestimation occurs at slower rotation speeds for larger displays. The interaction of speed and number of items is significant in the results of experiment 1. This indicates that it is not velocity per se but some other stimulus attribute is responsible for the overestimation of the number of moving items. The most likely candidate seems to be temporal frequency. Figure 5b shows that the temporal rate, which is called here 'flicker entry' and defined as the product of the rotation speed and the number of items, determines an almost constant threshold for the onset of the illusion in all different conditions. There are several studies consistently indicating that our visual system is more sensitive to the 'temporal rate' of moving stimuli than to their absolute velocity (Pantle 1974; Shorter and Patterson 2001).

In experiment 3, we compared an 'item counting' task with a 'colour counting' task. The results show that an increase in the perceived number of 4 rotating items can persist even when the items are marked with 4 different colours. This occurs without perceiving any increase in the number of colours or any repetition or duplication of the present colours. The question is: if there are 4 and only 4 colour-defined objects, then what is the colour of the extra item(s) at speeds above the threshold in the counting task? Subjects were not able to answer this question but they were sure that they had seen more than 4 objects rotating. This result leads to a discrepancy in the perception of spatiotemporal properties and feature properties of moving objects, which will be discussed later.

How can the MIO be explained? This phenomenon could be interpreted in two principally different ways. First, we could regard MIO as a 'perceptual' illusion and assume that some low-level perceptual mechanism generates additional visual items in high rotation speeds. So, the observer would 'see' the increased number of items and as a result count them mistakenly. It has been known for over a century that visual percepts of bright moving objects have a repetitive nature, so that a single isolated moving object is trailed by an extensive blur, containing a succession of lighter and darker regions. This phenomenon has been referred to as 'Charpentier's Bands' (McDougall 1904). Early studies of Charpentier's Bands were conducted under scotopic conditions but a more recent study replicated the same effect under photopic conditions (Chen et al 1995). Early explanations of this phenomenon attributed these percepts to the rhythmic discharges observed in some retino-geniculo-cortical neurons and recently Purushothaman et al (1998) proposed a computational model to simulate retino-cortical dynamics which could explain Charpentier's Bands and some other related phenomena. We suppose this classic phenomenon may provide an appropriate explanation for the observed results of MIO in future studies.

The second way of interpreting MIO is to regard it as an error in the counting process itself. Many authors identify three (Dehaene 1992; Gallistel and Gelman 1992) systems for enumerating items. The most obvious is proper counting, where items are individuated and tallied one at a time (Fuson 1988; Gelman and Gallistel 1978; Towse and Hitch 1996; Warren 1897). This works well for static displays when there is enough time to inspect and count. An alternative strategy is to identify the geometrical pattern of the items and this works well for small numbers of items (say, up to 6) that have characteristic organisations (Mandler and Shebo 1982). This pattern identification can be used to enumerate items in even very brief displays, as all the items are treated in parallel. This is a possible mechanism underlying the rapid enumeration of small sets (subitising) (Kaufman et al 1949). However, there is good evidence that subitising itself is a kind of pattern recognition (Wolters et al 1987). Finally, for larger numerosities when only a limited time is available, some propose an analogue number system that makes rapid judgments (Dehaene 1992; Dehaene and Cohen 1991; Dehaene et al 1990; Gallistel and Gelman 1992). This system transduces the quantity of the input numerosity to an implicit analogue magnitude scale.

The rotating displays used here can support proper counting at slow speeds and can also have easily recognisable geometry, again at low speed. Higher speed appears to decrease the accuracy of both of these processes. Enumeration of visual objects requires all objects to be individuated and indexed independently. Pylyshyn in his FINST theory (Pylyshyn 1989, 2001; Pylyshyn and Storm 1988) provided some evidence that the ability of individuating and indexing of objects is limited. Thus, it is rational to expect enumeration errors when the visual system cannot individuate objects properly. Verstraten et al (2000) have shown that individuation and tracking of even a single item among 4 to 12 items moving along a circular path breaks down at about 7 Hz, independently of the number of items. This threshold rate is the temporal rate (the product of the number of

923

items and the rotation speed) somewhat higher than the 5 Hz found in this study (figure 5). Counting of all items requires each item to be individuated and then marked so that it is not recounted. It is reasonable that the maximum speed at which this can occur can be lower than the rate for individuating only a single item in a display. Therefore, as the entry rate (figure 5) is the critical factor for the MIO effect, it is possible to consider the MIO as a consequence of a systematic recounting error, which increases as entry rate exceeds the critical 5 Hz value. This explanation implies that the proper counting system can track the individuated items up to a critical rate. As the rotation speed exceeds this critical rate, the counting system would encounter a recounting error and the magnitude of this error increases as the entry rate rises. There are also other studies supporting a low temporal frequency limit on individuation of objects. Holcombe et al (2001) have shown a 'midstream order deficit' in determining the sequence of repeatedly presented visual items at rates as slow as 5 items per second. Their results suggest that the observed deficit in determining the order of visual items is due to attentional temporal limitations in individuation of successive visual events and initiation of order encoding. Furthermore, Holcombe (2001) in a remarkable study has shown that alternation of two images in the same location can result in the simultaneous experience of both, accompanied by a sense of transparency. He also provided evidence that the simultaneous perception of both images is due to a purely temporal perceptual transparency mechanism and cannot be explained by simple 'summation' of the two images. This perceptual transparency mechanism may contribute to MIO illusion by providing transparent perceptual images of the visual items at 'different' locations when their temporal rate exceeds a limiting value. This transparent image may cause the number of moving items to appear larger; however, as the number of perceived items is not an integer multiple of the actual item number, a simple linear transparency mechanism is not sufficient for explaining MIO and we have to consider a 'nonlinear' nature for this transparency mechanism. Although this nonlinearity is consistent with Holcombe's results, it needs further investigation if one wants to consider it as a possible explanation for the MIO effect.

In experiment 3, rotating objects were marked by different colours. Consequently, it is possible to claim that 're-individuation error' cannot completely explain the MIO illusion because the rotating items were already individuated by their colours in this experiment and the visual system should not have encountered a recounting or re-individuating error. Hence, the presence of the MIO effect even in this condition weakens the 're-individuation' theory. However, the speed threshold of MIO is slightly increased in this experiment. Nevertheless, the FINST theory claims that spatiotemporal indexing and feature-location binding are separate mechanisms, and there are some lines of evidence that support this idea (Bahrami 2003; Saiki 2003). It is therefore reasonable to accept that the observer can count the number of colours of objects correctly—not to see any colour duplicated—while she/he is not able to index the rotating items properly and, therefore, recount them mistakenly.

If proper counting cannot be accurate above a certain speed, why not geometrical patterns? When objects are stationary, human pattern vision is exquisitely accurate; however, a number of studies have shown that pattern recognition is impaired for moving objects (Anstis et al 1999; Chung and Bedell 2003; Levi 1996). Also, our informal observations of rotating patterns of 3 to 6 items indicate that, at even very slow rates of rotation, the characteristic triangles for 3 items, or the squares, pentagons, and hexagons, for 4, 5, and 6 items all become circles. Apparently, it takes some time to establish the corner-to-corner links that define these simple geometrical shapes, and that time is not available in the rotating patterns. All are seen as traveling the circular path and this organisation supersedes the pattern geometries that would have revealed the numerosity of the items.

Another possibility in the MIO effect is the contribution of the analogue system. When the two other counting systems are unable to work accurately for the rotating patterns, numerosity judgment may be left to the analogue system. In judgments of large, dense displays, typically attributed to the analogue system, numerosity is often underestimated (Allik and Tuulmets 1993; Mandler and Shebo 1982). However, some experiments have revealed that spatial regularity, which is also present in our stimuli, will lead to overestimation of numerosity (Ginsburg 1976, 1978, 1991). The analogue system is not able, in principle, to estimate the number of elements in a display. Instead, some other stimulus attribute is estimated which could serve as the best available estimation of numerosity. Allik and Tuulmets (1991) have proposed that the numerosity of randomly distributed objects is estimated on the basis of the phenomenal impression of the area occupied by these objects. Results of experiment 2 provide a hint that the critical factor in MIO is the temporal rate. This temporal frequency is a good measure of the occupied area in the spatiotemporal domain and indicates that the observers may estimate temporal frequency of the stimuli as a substitute of numerosity for moving stimuli.

In this paper we attempted to investigate some essential and determining factors of the motion-induced overestimation phenomenon. This effect is a systematic error in enumerating rotating objects above a certain temporal rate. The possible underlying mechanisms that could be responsible for this error are discussed. However, at this moment we cannot select any of the discussed possibilities as the appropriate explanation for this phenomenon. There are still many unanswered questions about this effect: Is MIO special for rotating visual items? Do directly moving items show the same effect with the same strength? Is it a perceptual illusion or a counting mistake? ... Further studies are necessary to explore this visual effect more and to provide a theoretical framework that can explain MIO properly.

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