Title

Invariant Representations of Mass in the Human Brain and Its Effects on Inferences on Physical Collisions

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Abstract

From the moment they are born, infants begin to build an internal model of their physical world. This understanding of physical laws, commonly referred to as intuitive physics, develops over time, enabling individuals to successfully explore and interact with their surroundings. However, the cognitive mechanisms through which humans acquire this understanding of physical quantities, such as mass, are unknown. This paper discusses current understanding of a distinct but foundational part of the intuitive physics engine, mass representation. Current research has localized mass representation to dorsal frontoparietal, ventral-temporal, and dorsal premotor areas of the cortex. However, upon thorough literary analysis, the regions primarily responsible in this process have been narrowed down to the frontal and parietal regions. The extent to which these brain regions are responsible seems to be task dependent, opening avenues for further research to investigate the regions activated during other tasks involving different physical characteristics.

Introduction

Through early development, infants hone their understanding of the laws of physical interactions, updating their innate knowledge of how objects interact with the world. This innate understanding of physical laws and quantities is thought to be a result of the brain's intuitive physics engine, which enables individuals to make predictions about objects in motion. This prediction model enables individuals to quick responses in situations without conscious thought. The intuitive physics engine is believed to be located in several areas of the cortex, either the dorsal fronto-parietal cortex, which is involved for action planning, or the ventral-temporal cortex, which engages in object perception. For example, when you spill a glass of water, you would automatically know to catch the glass, and not the water.

However, this intuition is not entirely innate. Research suggests that infants are born with certain baseline expectations of how objects interact in physical space (Hespos, Ferry, Anderson, Hollenbeck, & Rips et al, 2016) and the ability to manifest predictions of objects and their interactions (Baillargeon 1998). Over time, infants update and develop their prediction ability to mirror that of adults. Evidence for intuitive physics is seen in infants as young as 2 months old (University of Missouri-Columbia). These infants demonstrate knowledge that objects will fall if they are without support and that hidden objects do not cease to exist when placed out of view. At 5 months, infants demonstrate the expectation that nonrigid objects like sand or liquid are not solid objects. In an experiment, 11-month-olds also demonstrate an understanding of the weight-compression rule which infers that heavier objects placed on a compressible platform will compress the platform more than a lighter object will (Hauf et al.).

Throughout development, infants amass a deeper understanding of intuitive physics and eventually hone this understanding into adulthood to form a fully developed intuitive physics engine. Fischer, Mikhael, Tenenbaum, and Kanwisher used a series of experiments on adult subjects to narrow down the regions of the brain that were recruited for intuitive physics understanding.

The first of these experiments was performed on 13 subjects (all right-handed, all with normal or corrected to normal vision). Each subject was shown 6-second movies of “towers” made of yellow, blue, and white blocks, which were all positioned so that the tower would be unstable and would tumble if gravity were to take effect (Fischer et al, 2016). This tower was placed on a circular floor, half of which was green and the other half red. The camera panned 360 degrees around the tower, giving subjects a full view of the tower’s makeup, and were instructed to imagine how the blocks would fall with the influence of gravity; specifically, whether more blocks would fall on the red side of the circle or the green side.

The second experiment was performed on the same subjects as the first, but the stimulus was altered: 10-second movies of red and blue dots moving in a square arena were shown (Fischer et al, 2016). The dots’ movements were dictated by Newtonian physics, elastic collisions, or social goals that had been assigned to the dots. The subjects were instructed to generate expectations for how dots would behave based on the physical or social behavior, as well as predict how the dots would behave during a mental simulation period.

The third and final experiment was a passive task assigned to 65 new subjects. The stimuli were 3-second movies depicting faces, bodies, scenes, objects, and other scrambled objects (Fischer et al, 2016). Subjects were simply instructed to watch the stimuli appear onscreen as experimenters observed their brain activity through fMRI.

The regions of the brain associated with these intuitive models were narrowed down to be the frontal lobe (problem-solving, judgment) and the parietal lobe (integration, interpretation of sensory information) (Fischer et al, 2016). These regions were found to have higher activation during physical reasoning tasks than during non-physical discrimination tasks from the same stimuli (Fischer et al, 2016). Likewise, these regions have been associated with action planning, and their activation during physical reasoning tasks highlights the importance of spatial awareness in action planning (Johansson and Flanagan, 2009; Gallivan et al., 2014; Evarts and Thach, 1969; Loh et al., 2010; Chouinard et al., 2005; van Nuenen et al., 2012). Although Fischer's fMRI study found that these regions are associated with intuitive models, it is not clear exactly what they actually represent about the physical events that they observe. There are two possible ways that the frontal and parietal lobes are involved in the processing of intuitive models: a pattern-recognition approach or a generalized engine for physical simulation. To determine their involvement in physical reasoning, three experiments were conducted studying object mass and its relation to neural representations during physical reasoning tasks. The data was collected using fMRI while the participants were making predictions in each of the experiments.

The variable mass was the main focus of this experiment due to mass being an integral characteristic of all physical objects. Current research has explored the frontal/parietal regions as well as the occipitotemporal complex as primary domains of activation in mass representation calculations. Using the study within the Fischer et. Al (2016) paper as a framework, which observed functional recruitment of the frontal and parietal regions, our study analyzes the approaches and results of further research that aimed to locate the intuitive physics engine. The concept of one's physics engine centers around the idea that the brain produces a series of approximate, yet probable simulations to deduce physical inferences about objects in motion. Fischer et. al, within their paper delve into the regions of the brain at work within this given physics engine when observing and making predictions about specific active scenarios. Their study aimed to deduce whether this physics engine occurred within a specific region of the brain that is specialized in a specific function or whether there is an overlap between regions and certain parts of the brain are employed that are also known to be engaged in other functions. Their study involved asking participants holding the stimulus constant and varying the task, one holding the task constant and varying the stimuli, and one contrasting passive viewing of engaging movies that contained extensive physical content vs. non physical content. Through these studies it became evident that physical scene understanding engages a systematic set of brain regions, namely bilateral frontal regions (dorsal premotor cortex/supplementary motor area), bilateral parietal regions (somatosensory association cortex/superior parietal lobule), and the left supramarginal gyrus.

Occipitotemporal Complex

Research into the cortical locations that code for physical inferences is novel and consequently lacking in sure certainty. Object mass prediction, with and without regards to action planning, however, has been shown to be linked to various regions of the brain, with some researchers showing the recruitment of the occipital lobe--despite mass being a nonvisual property. Fischer et al (2016), as stated, used fMRI to observe the activated networks while observing physical scenarios, effectively visualizing the intuitive physics engine. Fischer et al’s (2016) look into the intuitive physics engine yielded systematic patterns of activation in the frontal and parietal regions as well as the left supramarginal gyrus. The research was used as a foundation for further experimentation to observe the pathways of intuitive physical inference in order to identify the necessary areas for these innate higher order observations and calculations.

Many studies have specifically looked at mass representation as a function of the intuitive physics engine. Observations and mental representations of mass based on visual and behavioral cues govern the way an individual interacts with that object. Using mass representation as a vehicle to observe the intuitive physics engine Gallivan et al (2014), as well as Buckingham et al (2018), postulated that the occipitotemporal complex might play a role in such understanding of physical scenarios and predicting outcomes, as the ventral visual stream is responsible for object perception. Object pattern recognition, specifically with regards to motion, plays a significant role in the development of intuitive physics understanding. Schwettman et al (2019) and Loh et al (2010) similarly looked at mass representation in the frontal and parietal regions, trying specifically to locate individual areas and networks that are functionally necessary in forming an invariant mass representation with and without action planning. The analysis of these experimentation methods and the interrelation to the findings of Fischer et al is the goal of this discussion of the location of the intuitive physics engine.

Gallivan et al (2014) performed an experiment that employed fMRI and multivoxel pattern decoding techniques to locate and determine the cortical regions that predict object mass prior to lifting an object. While Fischer et al (2016) observed inference and prediction based on physical scenarios, Gallivan's study used action planning as the catalyst for mass representation. Object mass inference is necessary to successfully perform a lift by predicting how much force is necessary to carry out that action. They theorized that because the ventral visual pathways account for the perception of object form and recognition, that the same pathway might also contribute to representations of object weight, despite it being a nonvisual property. The participants of the study were told to lift each object of varying weights six times before running through "six individual plan-and-lift trials with that same object" (Gallivan 1866). The preparatory session becoming familiar with the object was termed the "interaction phase." When analyzing the participants' abilities to predict object weight before the action, activity patterns throughout the planning periods were extracted from the somatomotor regions of interest--namely the contralateral primary motor cortex (M1), dorsal premotor cortex (PMd), and somatosensory cortex (SSc)--as well as the lateral occipital complex (LOC) located within the occipitotemporal cortex (OTC). These mass and object sensitive areas were the primary focus because of their likely implication within the intuitive physics engine, and specifically mass inference. Activity in M1 and PMd aligned with the researchers' expectations that these regions would show activity patterns that "reliably discriminated the weight of the object to be lifted," while the pattern of the SSc showed stimulation only during the execution period of the action (1866). The second experiment performed by the researchers used different textures to indicate mass. Activity in the lateral occipital complex was found throughout these trials, indicating a functional role of the LOC when texture, a visual property, is suggestive of mass. Their results indicated that "the integration of visual and motor-relevant object information occurs at the level of single OTC areas and [provides] evidence that the ventral visual pathway is actively and flexibly engaged in processing object weight, an object property critical for action planning and control" (Gallivan et al, 2014). These results propose additional areas of interest to Fischer et al's (2016) assertion that the functionally essential regions of the brain in mass inference lie in the frontal and parietal regions. Although mass is a nonvisual property of objects, when visual properties are necessary to perceive in order to form a mental representation of object mass, the lateral occipital complex, within the ventral visual pathway, is possibly recruited to contribute to that representation.

Buckingham et al (2018) cites the Gallivan study in their more recent experimentation into the role of the lateral occipital complex in the representation of mass within the brain, again specifically with regards to prediction and action planning. Their study sought to answer whether the LOC plays a functional role in object mass processing or whether it receives information downstream from the somatosensory and motor regions. Like Gallivan et al (2014), the Buckingham study differed from Fischer in using action planning as the reason for mass representation. Buckingham et al (2014) explored this potential association of the LOC to mass inference networks with the participation of a woman with neurological deficits resulting from a prior stroke. The woman, M.C., had extensive bilateral lateral occipital complex lesions resulting in no activation of the LOC. The researchers theorized that if the LOC is necessary for predicting object weight before lifting, a patient with extensive bilateral lesions will not be able to accurately anticipate object weight based on visual size cues, as the ventral visual pathway would be impaired. Their study used M.C. as the experimental group and a group of neurologically healthy age-matched controls. These participants allowed them to confidently discriminate any difference in perception and determine the source of that distinction to be the inactivation of the LOC. Initial finger-tip pressure when lifting objects (which varied in sizes) was measured and assumed to be congruent with their predicted weight of the object based on the size cues (Buckingham et al, 2014). The objects had the same mass, but naturally contributed to a phenomenon called the size-weight illusion, where the smaller objects seemed heavier even though the mass was the same as the larger objects. Similar to Fischer et al (2016) and Gallivan et al (2014), this study used an orthogonal property (size) as a visual cue for mass, just as Fischer used shape and Gallivan used texture. The researchers determined that if the LOC was necessary to predict weight based on appearance, that M.C. would not readily experience the size-weight phenomena and be able to use size cues to determine a grip force necessary to lift the objects (Buckingham et al, 2014). The results indicated that M.C. had no notable deficiencies in using size clues to predict object weight, and she experienced a strong size-weight illusion, similar to the neurologically healthy participants. This illusion was evident in the participants systematically using a greater initial grip force for the bigger objects, therefore associating the larger size with a possible larger mass. The researchers concluded that the LOC does not causally play a role in object weight representation because of the alignment between the initial grip force exerted by M.C. as well as the other participants. Contrary to the assumptions of Gallivan et al (2014) and congruent with Fischer et al (2016), the LOC, and other object-selective areas of the ventral stream, are downstream recipients of weight related information that is computed elsewhere in the brain (Buckingham et al, 2014).

Frontal and Parietal Premotor Cortex

While prior studies, like that of Gallivan et al (2014) and Buckingham et al (2014) focused on neural decoding of mass confined to a particular stimulus and action, Schwettmann et al (2019) expanded on this research by applying this generative model of intuitive physical inference to various diverse scenarios and stimuli. Schwettmann et al (2019) within their research, delve into the automaticity of neural representations using fMRI and motion tasks to understand “individually candidate regions engaged in physical reasoning and invariant representations of mass in these regions” (Schwettmann et al 2019). There were three different experiments done within the study, and in regards to mass inference, the study theorized that object mass could be decoded from neural activity in previously described candidate physics regions while participants performed a mass inference task. In a group of six subjects, each were shown three movies of real objects splashing into a container of water, being blown across a flat surface by a hairdryer, and falling onto the soft surface of a pillow. During a response period the subjects were directed to indicate their predicted weight of the observed object with a button press (light or heavy) in response to the motion witnessed within the videos. When analyzing the data derived from the participants, responses reflected their predictive ability to deduce whether an object would be light or heavy. Through the use of fMRI, Schwettmann et al (2019) identified brain activity within the frontal and parietal regions of the brain used for physical inference throughout the tasks. This data further emphasized the role of visual cues within a scene, functioning as primary sensory information, as indicators of the nonvisual physical properties of an object, like mass, and generalized aspects of the object's physical dynamics. The results found that the network of frontal and parietal functional ROIs form a generative model of physical objects and their operational dynamics, which aligned with results in prior studies performed by Fischer et al (2016). This understanding led them to deduce that specific regions of the brain contribute to the predictive aspects of one’s neural physics engine. The data also emphasized that there was no trace of invariant mass representation in ventral visual pathways such as the LOC and OTC, which are necessary for perception of visual properties of objects. A primary conclusion that can be made from this paper centers around the notion that an intuitive physics engine utilizes brain regions outside of the ventral stream and primarily the frontal and parietal regions, with regions of the ventral stream, therefore, receiving information regarding object mass downstream.

Loh et al (2010), within the paper, *Information about the Weight of Grasped Objects from Vision and Internal Models Interacts within the Primary Motor Cortex* specifies more distinguishable regions within the brains that are employed when performing mass determining motions, both in the presence of absence of visual cues. The paper produced by Fischer et al

(2016), provides a more generalized depiction of brain activity that occurs over a wide array of stimuli, while Loh et al (2010), hones in on mass representation within the brain and its correlation with visual cues that give insight into the object's weight. The Fischer paper addresses this idea with it's conclusion that there are many avenues that are opened as a result of their study, one being whether there is a specific brain region that encodes for physical properties like mass and force. Aligning with the study produced by Fischer et al (2016), this study looked into the effect of sensorimotor memory on the corticospinal system when preparing to lift an object of an unknown weight, following the motion of grasping a heavy or light object. They sought to understand the role of how visual cues affect lifts of heavy and light objects, with respect to initial grip force, preceded by a lift of the same weight. Their theory drew from the idea that sensorimotor memory interacts with object weight prediction, so that in the absence of visual information, the corticospinal system will reflect and adapt to that of the previous lift. Participants were seated at a table with a turntable of 4 different glasses, two opaque and two transparent, with either a light (small) or heavy (big) object inside. A glass screen is placed in front of them that can switch between transparent and opaque, so that they cannot see the turning of the turntable and the order of the appearance of the glasses appears pseudorandom. When the screen turns clear, the participant knows to reach to grab the glass in front of them. Unlike the study produced in Fischer et. al (2016), which utilized fMRI to infer the regions of the brain that activity was present during physical inference tasks, Loh et. al, used MEP, or motor evoked potentials induced by TMS (transcranial magnetic stimulation), to determine the activity of the corticospinal system at three different intervals before the lift. As a result of their trials, the study deduced that when no visual cues were present or available to the subjects regarding the object's weight, the CSE relied on the weight of the object from a previous lift. However when preparing to lift an object when the weight was apparent, the sensorimotor memory from prior lifts was still present and active, yet was gradually suppressed and canceled out all together after visual cues became available and the visual information reached the corticospinal system. This is indicative that the corticospinal system is able to store information regarding the movements necessary to lift the weight, and can adapt its current state when visual cues become available to initiate a more accurate and proper response which is reflective of the excitability level of the muscle representations in the MEPs. Though previous papers attribute this theory to M1, or a portion of the cortical network involved in the storage of sensorimotor memory, this paper gives a more nuanced depiction of the possibility that M1 could store sensorimotor memory through modulation of the CSE involved in muscle representation. Whereas the paper produced by Fischer et. al (2016) investigated the overlapping of visual signals and the internal physics engine (i.e., asking participants about the color composition and the end result of a tumbling tower of blocks), the study performed by Loh et. al, looks more in depth into the overlapping role of visual cues and how that influences the amount of force produced when determining an object's mass. This study more prominently aligned with the portion of the paper produced by Fischer et. al (2016) that deduced that brain activity during a task that asked subjects watched pairs of dots moving within a square arena, and form physical inferences regarding their collisions, prompting brain activity in dorsal premotor cortex and supplementary motor area. These regions of the brain, coupled with the role of the primary motor cortex and the corticospinal system collectively function in a manner that works towards motor movement and the action planning that elicits that movement.

Similarly, the study, *Weight-Specific Anticipatory Coding of Grip Force in Human Dorsal Premotor Cortex,* centers around the role of the dorsal premotor cortex, located anterior to the primary motor cortex, and how it utilizes sensory information to prepare for physical activity and motion. More precisely, the study sought to further clarify the functional relevance of the premotor cortex in applying prior sensory information when anticipating the magnitude of grip force necessary to move an object in the presence of visual cues. Based on previous studies, these researchers deduced that the premotor cortex is responsible for predictive features of sensory information, more precisely in hand movements reliant on sensorimotor mapping rules. In response to this data, they used continuous theta burst stimulation, or cTBS, to disrupt the neural processing within the premotor cortex as participants were instructed to lift certain objects after a given visual cue. Using the conditioning and map approach, 11 healthy male subjects, averaged at age of 27, were used in the group being studied. Each of the males underwent two different trials in a neutral order, with each trial being identical aside from the cTBS application which varied in the intensity of the simulation. The experimental task required participants to grasp and lift a manipulandum with their right dominant hand. They then applied either cTBS (applied to the left dorsal premotor cortex) to disrupt the neural processing within the premotor cortex, followed by fMRI to understand and map the effects of cTBS on preparatory brain activity. During the fMRI period, the subjects were shown a visual symbolic pre-cue (S1), represented by a shape, that predicted whether they were going to lift a heavy or light object (red square for heavy, red circle for light). After the initial visual cue, they were presented with a second visual cue that gave insight into the weight of the object (green circle light object, green square heavy object). The subjects were then asked to perform the grip and lift test to determine if the anticipatory visual cues accurately predicted their movements. The results of the experiment indicated that the role of tCBS and the validity of the pre-cue had consistent effects on task performance. The cTBS ‘ensured that subjects used a visual mode of anticipatory force control' and enabled the researchers to establish the more specified association between the premotor cortex in the upscaling and downscaling of the applied force dependent on the visual cues. Unlike previous studies, Nuenen et al (2012), "anticipatory force scaling was challenged by introducing a conflict between two "predictive" visual cues," which enabled the study to isolate task performance that created somatosensory feedback that was consistent with the predictive information derived from the visual cue. The experiments presented in the study offer primary demonstration that the left premotor cortex is an attributable region within the brain to the anticipatory up and downscaling of an applied force in relation to an object's mass in the presence of visual cues. Seeing as the Fischer et. al (2016), paper provided a detailed depiction of the regions of the brain that are often active during action planning and the physical inferences of objects in motion, they fail to touch on the regions of the brain that apply to direct planning of force and motion in regards to lifting and grasping objects. The paper produced by Fischer et. al (2016) highlights the dorsal premotor cortex as being an attributable region in predicting how physical events unfold, and applies this idea more directly to the observation of physical objects in motion as opposed to Nuenen et. al (2012), which attributes this region to the coding of "predictive aspects of sensory information in the context of manual motor control" (Nuenen 5272) . Namely, sensory information being the role of visual cues and how those cues provide information regarding an object's mass. Nuenen et. al (2012), furthers this study of mass perception and inference, by investigating how this intake of sensory information guides one's grip force when lifting an object, and what regions of the brain work in conjunction with the dorsal premotor cortex throughout this process.

Discussion

These previously mentioned studies on the invariant representations of mass and physical characteristics in the brain provide important insight into the brain's intuitive physics engine. Upon deeper and more specific analysis of the various implicated regions, including the dorsal fronto-parietal, ventral-temporal, and dorsal premotor areas of the cortex, we begin to piece together the puzzle that makes up the brain's physics processing system, and namely the source of our intuitive physical reasoning. While a few studies entertained the idea that the occipitotemporal cortex also played a large role, this region was found to be not functionally necessary for mass interpretation. The extent to which various brain regions are responsible in object representation is seemingly task dependent, opening avenues for further research to be conducted to investigate the regions activated during other tasks involving different physics characteristics. Evidence from the discussed papers indicates that properties of objects such as form and motion are expressed in the dorsal cortex.

However, the papers discussed have their own drawbacks. In the study conducted by Buckingham and his colleagues the sample size was very small making it difficult to generalize the results to the general population. Additionally, this study begs the question if specific areas of the lateral occipital complex are implicated in object weight perception rather than the whole, and if more lesions in the studied region lead to less perception of object weight in a linear fashion. Likewise, in the study, *Weight-Specific Anticipatory Coding of Grip Force in Human Dorsal Premotor Cortex* the subject pool for the trial was not a very diverse set of individuals, and with 2 error trials per fMRI session for such a small subject pool the reliability of the results from this study are brought into question with further studies into this area likely needing to be done.

As a result, in the future more studies need to be done to validate the proposed models of the studied papers. A major question is what type of object properties are processed along the dorsal pathway, and the extent to which the dorsal and ventral pathways represent redundant or unique object information? The functional significance of dorsal stream object representations is unclear, and in future studies this should be a major area of focus to decipher its significance. Once we identify all functional components and the corresponding regions responsible for their processing, we may achieve a deeper comprehension of the intuitive physics engine in the brain as a holistic, highly interconnected system.

References

Baillargeon R. 1998. Infants' understanding of the physical world. In: Sabourin M, Craik F, Robert M (Eds). Advances in Psychological Science Biological and Cognitive Aspects. 2 Hove, England: Psychology Press.

Battaglia, P.W., Hamrick, J.B., Tenenbaum, J.B. 2013. Simulation as an engine of physical scene understanding. PNAS 110:18327–18332. DOI: https://doi.org/10.1073/pnas.1306572110, PMID: 24145417

Buckingham G, Holler D, Michelakakis EE, Snow JC. 2018. Preserved object weight processing after bilateral lateral occipital complex lesions. Journal of Cognitive Neuroscience 30:1683–1690. DOI: https://doi.org/10. 1162/jocn_a_01314, PMID: 30024326

Fischer J, Mikhael JG, Tenenbaum JB, Kanwisher N. 2016. Functional neuroanatomy of intuitive physical inference. PNAS 113:E5072–E5081. DOI: https://doi.org/10.1073/pnas.1610344113, PMID: 27503892

Gallivan, J. P., Cant, J. S., Goodale, M. A., & Flanagan, J. R. (2014). Representation of object weight in human ventral visual cortex. Current Biology, 24, 1866–1873. DOI: https://doi.org/10.1016/j.cub.2014.06.046

Hauf, P., Paulus, M. and Baillargeon, R. (2012), Infants Use Compression Information to Infer Objects' Weights: Examining Cognition, Exploration, and Prospective Action in a Preferential‐Reaching Task. Child Development, 83: 1978-1995. doi:10.1111/j.1467-8624.2012.01824.x

Hespos, S. J., Ferry, A. L., Anderson, E. M., Hollenbeck, E. N., & Rips, L. J. (2016). Five-Month-Old Infants Have General Knowledge of How Nonsolid Substances Behave and Interact. *Psychological Science*, *27*(2), 244–256.

https://doi.org/10.1177/0956797615617897

Loh, M. N., et al. “Information about the Weight of Grasped Objects from Vision and Internal Models Interacts within the Primary Motor Cortex.” *Journal of Neuroscience*, vol. 30, no. 20, 2010, pp. 6984–6990., doi:10.1523/jneurosci.6207-09.2010.

Van Nuenen, B. F., et al. “Weight-Specific Anticipatory Coding of Grip Force in Human Dorsal Premotor Cortex.” *Journal of Neuroscience*, vol. 32, no. 15, 2012, pp. 5272–5283., doi:10.1523/jneurosci.5673-11.2012.

University of Missouri-Columbia. "Babies are born with 'intuitive physics' knowledge, says researcher." ScienceDaily. ScienceDaily, 25 January 2012. <www.sciencedaily.com/releases/2012/01/120124113051.htm>.