The role and benefits of cognition and perception in medical imaging

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Abstract

Introduction

In an era of unprecedented technological advances across the field of medical imaging, it is critically important to understand the cognitive and perceptual functioning of the "human in the loop," the clinicians who make the final decisions on detection, diagnosis, and treatment. However, research on the cognitive and perceptual processes underlying clinician performance is chronically understudied. In September 2019, the National Cancer Institute (NCI) convened the "Cognition and Medical Image Perception Think Tank"[1] in order to advance research on medical image perception and cognition. The Think Tank brought radiologists and pathologists together with researchers working in medical image perception and adjacent fields of cognition and perception, along with representatives from interested federal government agencies (including NCI, National Institute of Biomedical Imaging and Bioengineering, U.S. Food and Drug Administration, U.S. Department of Homeland Security) to address the Think Tank's key objectives (see Table ??) through panel discussions, constructive discourse, idea generation, and problem-solving. Panel discussions were guided by critical questions generated by the participants themselves in advance of the meeting. Here, we report on the Think Tank's deliberations and highlight opportunities to expand the research in medical image perception and cognition.

Objectives
1. Identify research gaps and critical unsolved problems in pathology and radiology, from the perspective of clinicians.
2. Discuss ways to address these clinically-informed questions through cognitive and perceptual research.
3. Identify barriers that hinder collaborations between researchers and clinicians and identify potential solutions.
4. Identify and discuss ways to elevate psychology's profile within the medical image community and broader communities.
5. Identify future goals and identify strategies to evaluate progress.

Table 1. Think Tank Objectives {#tbl:Objectives}

Identifying research gaps

Detection and diagnosis rely on clinicians[2] searching for abnormalities in medical images. Across the many ways to acquire images (from light microscopy to magnetic resonance) and present them (e.g., via glass slides or computer workstations), clinicians are confronted with similar perceptual and cognitive challenges. Clinicians are tasked with bringing to bear a vast amount of medical knowledge, together with contextual information about the patient (e.g., referring physician's information, prior report, prior medical history, genomics information) in order to interpret highly complex and variable images quickly and accurately. This is a highly challenging endeavor. Clinicians face many difficulties, from information overload to repeated interruptions to clinician burnout, that in turn are closely associated with health care quality, patient safety, and financial burdens on practices [**???**,1,2]. Even under ideal circumstances, human observers are bound to make mistakes. Errors, both false positives and false negatives, are a reality in both radiology [3,4,5] and pathology practice [6]. The majority of diagnostic errors in radiology can be traced to perceptual and cognitive factors (Berlin & Berlin, 1995; Smith, 1967). The same is probably true in pathology, though there is much less research in this area (Raab et al., 2005). Improving the accuracy of diagnosis requires an understanding of the perceptual and cognitive mechanisms underlying the performance of clinicians. Additionally, cognitive and perceptual principles and approaches should be applied to address issues concerning clinicians' work environment and well-being.

What research should we encourage in order to improve clinicians' diagnostic accuracy, work environment, and well-being? The first challenge for the Think Tank participants was to identify the research gaps and critical unsolved problems in pathology and radiology, from the perspective of clinicians. The primary challenges identified by the clinicians were information overload and integrating large amounts of information from various sources.

For example, the transition from the analog to digital eras has meant a qualitative change in the nature of the radiological problem. A radiologist scrutinizing a single chest X-ray for a lung nodule is trying to extract a target with a very low signal:noise ratio (SNR) from a single image. The same radiologist reading a chest CT is searching for a target with a fairly high SNR in a scan comprising thousands of images (slices). In addition, the radiologist must now incorporate into her decision information from outside sources, such as electronic health records and genetic panels, that may not have been available in the past. Furthermore, the decisions that clinicians have to make have gotten more complex as precision medicine has advanced. A pathologist now might have to indicate not just whether something is a tumor or not, but if the tumor is hot or cold, likely to be responsive or non-responsive. The cognitive capacity of the clinician, in contrast, has not changed, and the time pressure has only gotten worse. What are the effects of information overload on medical decision making and decision quality? Are there technical solutions or decision-making aids or strategies that could be used to efficiently integrate complex information? For example, psychologically distancing oneself from information has been shown to improve non-medical decision-making (Fukukura et al., 2013). What is the applicability of decision strategies to real world practice? The cognitive and perceptual challenges of the clinicians' role, and the implications for practice, are poorly understood at present.

Task shifting was another topic identified by the Think Tank participants. Interruptions and distractions from a variety of sources (e.g., texts, email, pager, colleagues, telephone) may lead clinicians to miss or fail to report important findings. Another form of task shifting is when clinicians move from case to case, different organs, while using various image modalities. There is no research on whether task shifting in medical imaging creates adverse sequential consequences and/or how to mitigate these effects.

As one might expect from the above descriptions, the workload for clinicians has increased, and physical and mental fatigue of clinicians are at unprecedented levels, contributing to both perceptual and interpretive errors. Fatigue can manifest as attention errors, such as when a clinician scrolls too fast through multi-slice or volumetric images, which may give the false impression that the clinician has sufficiently viewed the case. Additional errors can result from lack of focus, getting easily distracted, and/or failing to record what is perceived. These errors caused by physical and mental fatigue become more apparent at the end of the day. Multiple studies have reported a decrease in detection accuracy due to fatigue (for a review, see Waite et al., 2017) but translational research needs to be conducted to mitigate fatigue effects in real world practice.

Interpretative errors can occur from a variety of sources. For radiologists, several categories of tumors can be difficult to interpret, such as when there is a subtle gradient (i.e., when it is difficult to notice subtle changes or new lesions) from benign to malignant tumors, malignant to benign tumors, and when benign tumors mimic malignant tumors. Additionally, it is also often difficult to interpret or connect two dissonant findings (e.g., adrenal nodule with a lung mass) and the clinician ends up failing to link findings and report a complete picture. Research should focus on understanding the perceptual and cognitive underpinnings of these type of cases to help mitigate interpretation difficulty.

Artificial intelligence (AI) tools are often proposed as a solution to the challenges facing clinicians. However, there is a mismatch between what clinicians need from AI and how AI is typically developed. AI solutions are often pitched as "outperforming" the clinician, implying that AI systems are on the cusp of replacing the clinician (Mukherjee, 2017), or at least serving as an equivalent reader (McKinney

et al., 2020). This stems from an incomplete picture of the clinician's job. A better approach would be to develop AI as a tool to automate the data reduction process, extracting the information that will aid the clinician's decision process. For example, when reading pap smears, cytotechnologists can sign off on cases that are unequivocally negative, leaving the cytopathologists to focus only on cases with potential abnormalities. AI could usefully fulfill this sort of role, and potentially automate quality assurance (QA) procedures. A useful framework is the "diagnostic cockpit of the future", described by Krupinski et al. (2019) as a set of tools to "aggregate, organize, and simplify medical imaging results and patient-centric clinical data." This metaphor underscores the role of AI in helping to winnow the information available to the clinician and present only the most clinically relevant information in the clearest way possible. In order to accomplish these goals, AI should be developed within a broad interdisciplinary context. Clinical, perceptual, and cognitive perspectives are all needed in the development process, rather than treated as an afterthought.

Addressing clinical questions through perceptual research

There's an old science joke that goes something like this: A dairy farmer is looking for ways to increase the output of his cows, as cheaply as possible. He consults an agronomist, who recommends changes to the feedstock and new equipment which will require major investments. He turns to a biologist, who suggests hormone treatments that will be cheaper, but still involve an outlay of more money than he wants to spend. Finally, he turns to a physicist, who promises a free solution. He eagerly asks her to explain her idea. She begins, "First, assume a spherical cow with radius r and mass m, uniformly emitting milk in all directions..."

To many clinicians, perceptual research on medical image interpretation can sometimes seem like the equivalent of a spherical cow emitting milk in all directions. Perceptual studies typically abstract away from the specificity and messiness of the clinical reading context in order to gain experimental control. Complex stimuli are simplified, narrative reports are replaced with binary responses, clinical history is absent, and the life-and-death stakes of the clinic are removed. Consider Wolfe and Horowitz's work on the effects of prevalence [7], in which amateur observers drawn from the Cambridge, MA community searching for the letter "T" concealed among arrays of "L"s are meant to have some relevance to radiologists searching for cancerous lesions in mammograms or lung CTs. Traditional medical image perception research may skew closer to the clinical experience, using experienced professional readers and real cases. Even so, the consequences for a missed target or unnecessary callback are not the same. Furthermore, in perceptual research each trial in a given experimental condition is assumed to be equivalent to other trials (because stimuli are typically randomly and algorithmically generated), to the clinician, each case is unique, leading to a reluctance to generalize. All of these factors may lead to a certain skepticism in the clinician community about the value of perception research, especially in the face of the difficulties raised in the *Identifying Research Gaps* section.

There is a trend in medical image perception studies where the researcher follows a "Reverse Translation" model to assess clinical problems. This is where a researcher observes a problem in the clinic that resembles an area of perception research they are doing in the lab or has familiarity with. The researcher will then develop lab versions of the problem to study the basic perceptual and cognitive science principles of the problem. These studies will sometimes use observer models or undergraduate students as they are more efficient to use lab studies as clinicians time is limited. After many iterations of working out the basic science and once the researcher has a good working hypothesis, they will then go back in the clinical setting to test their hypothesis. A major issue with this model is that the problems that are being assessed are not the critical issues that clinicians actually want answers to. We propose researchers adopt a "Reverse Translation Phase 2" model, where researchers investigate problems and that are important to the clinician and then follow the same "Reverse Translation" procedure.

Within the "Reverse Translation Phase 2" model, there are key assumptions that allow for the translation of principles studied and derived from lab studies to the clinical setting even when clinicians or medical images are not being utilized. First, clinicians and non-clinicians have the same visual systems and perceptual and cognitive faculties that allow us to process and interpret stimuli. Second, artificial tasks and stimuli capture the key elements of the clinical tasks and stimuli. Going back to the work on prevalence effects, studying the effect of low prevalence on radiologists' performance with a reader study would take years to complete and would put a substantial burden on clinicians. Medical image perception studies have replicated the prevalence effect in the lab setting using non-clinician readers and non-medical image stimuli [8], demonstrated low prevalence influences non-clinician and clinician readers' response criteria [9,10,11], and have proposed potential solutions to mitigate prevalence effects [12,13,14,15].

Enabling collaborative transdisciplinary research

Successful collaborations between clinicians and perception researchers[3] are essential to address the dynamic challenges that clinicians face. The study of medical image perception is an inherently trans-disciplinary enterprise, often requiring collaborations between clinicians, medical physicists, computer scientists, biomedical informatics engineers, and psychologists. Historically, medical image perception research was led by clinicians, notably William Tuddenham and Harold Kundel [16,17], who championed applying principles from psychology and other disciplines to advance medical image research (Tuddenham, 1969). These collaborations were easier to initiate in an era when perceptual psychologists (such as Elizabeth Krupinski at Emory University, or Philip Judy at Brigham and Women's Hospital) were embedded in radiology departments. These researchers were intimately familiar with the problems and perspectives of clinicians, and could also easily find collaborators. Unfortunately, this model has fallen out of favor. Today, multiple barriers hinder collaborations between perception researchers and clinicians (see Table ??). Here, we expand on the challenges and potential solutions that were discussed.

The main constraint on successful collaborations is the limited time clinicians have to be active researchers and/or participate in reader studies. Collaborations should be designed to respect the clinician's schedule, and projects should be developed around common interests of both parties. Resources should be available for clinicians through incentives and grant mechanisms. Incentives for clinicians participating in reader studies are either nonexistent or not beneficial for the clinician. Think Tank participants proposed a number of possible solutions. An important step would be to provide incentives continuing medical education (CME) credit and/or CME in Risk Management for participating in research. In order to facilitate CME credit, an educational module should be created for participants. Possible objectives for this educational module could include education on classic visual search and interpretive errors (e.g., prevalence effects, satisfaction of search errors, satisfaction of report errors, cognitive biases) and fundamental perceptual or cognitive concepts relating to clinical practice (e.g., perceptual attributes of expertise, development of global processing, attentional mechanisms). A more ambitious suggestion is to create joint funding opportunities with the Agency for Healthcare Research & Quality (AHRQ), NCI's Healthcare Delivery Research Program and Behavioral Research Programs, and the National Institute of Biomedical Imaging and Bioengineering (NIBIB) to support collaborative research funding, protected time for clinicians committed to research, and/or mentoring junior research scientists.

Organizing "pop-up" perception laboratories at clinician conferences to recruit clinicians in reader studies has been successful in recent years [18], but sustaining these efforts will require partnering with national and regional medical conferences (e.g. American Society for Clinical Pathology (ASCP), Radiological Society of North America (RSNA), Society of Nuclear Medicine and Molecular Imaging, The Association for Medical Ultrasound), university medical centers, NCI designated cancer centers, and the American College of Radiology, to make medical image perception research a priority, and to

financially sustain perception laboratories. Perception laboratories at conferences could also be sustained through NIH R24 or R25 grant mechanisms.

Collaboration often develops serendipitously, and serendipity depends on proximity. For perception researchers who are not embedded within medical centers, opportunities to network or promote research though invited talks are limited. One solution would be to create a match-making resource to identify perception researchers, clinicians, conferences, private practices, and medical departments that are open to collaborative research. Contributors would indicate their areas of expertise and of interest, and the type of contribution they were interested in providing, such as participating in reader studies, inviting researchers to give talks at their institutions, providing image datasets, generating research ideas and providing feedback, or becoming investigators. Another idea is to bring perception science to the clinicians. While the primary purpose of a pop-up lab like the NCI Perception Lab at RSNA is to recruit clinicians as participants, these endeavors can also provide opportunities for exposing clinicians to perceptual research and sparking conversations between researchers and clinicians. These outreach opportunities could be expanded, perhaps by providing workshops on perceptual science at a variety of clinical meetings, where perceptual scientists could explain their research and exchange ideas with clinicians.

Accessing medical image datasets can be a challenge for perception researchers. Curating large image datasets is often time-consuming for the clinician and requires financial resources to undertake and sustain. Sharing images across institutions is difficult due to liability issues. Even access to image sets from large, government-funded trials can be arduous and depend on the preferences of the original PIs. Furthermore, access may be only for restricted uses, such as specific research projects, making it difficult to develop clinical tools. These problems could be addressed by developing templates for peer-to-peer research collaboration and sharing agreement.

There are also existing image repositories (e.g., NCI's The Cancer Imaging Archive, TCIA). These repositories may avoid the access difficulties associated with clinical trial image sets, but they often lack needed clinical context, appropriate annotations, and an efficient interface for navigating and searching for relevant images. One possible solution would be to emulate the Crowds Cure Cancer project, which was created in 2017 to address the lack of annotations in NCI's Cancer Imaging Archive. Crowds Cure Cancer recruited radiologists attending RSNA to identify lesions, lesion characteristics, and provide details regarding image quality. This professional crowdsourcing model could be a template for annotating other large medical image repositories. Involving perception scientists in the design of the project could help to ensure that variables important to perception studies were coded as well.

Another factor is the rise in recent years of AI approaches to medical image interpretation. If machines are going to be finding the lesions and counting the abnormal cells, then understanding how the human perceptual system interprets medical images is a waste of time. Even for clinicians who are skeptical about the potential of AI to replace them (or the timeline) may find that AI projects compete with perception research for their limited research time.

Barriers that Hinder Collaborations Between Researchers and Clinicians.
1. Time Pressures for Clinicians.

- Access to clinicians is limited in terms of collaborations and participation in reader studies.
- Incentives (i.e., CEM/RME Credit) should be provided to clinicians.| | 2. Lack of Networking Among Disciplines.
- Increase the probability of serendipitous collaborations by creating a "matchmaking" resource.| | 3. Limited Access to Image Datasets| | 4. What is the relevance of human perception in the face of AI?|

Table: Barriers to Transdisciplinary Research {#tbl:barriers}

Elevating the profile of medical image perception research

Elevating the profile of medical image perception research within the broader medical and scientific communities (e.g., government agencies, industry, advocacy groups, journal editors, review panels, study sections) is essential to ensure a sustainable future for this important research endeavor. Here we identify key essential elements for achieving this goal (see Table ??).

Creating a network of invested stakeholders (e.g., clinicians, academia, biomedical informatics, government and regulatory agencies, medical centers, industry, conferences) is critical to support an awareness program promoting education, collaboration, and research. Clinician advocates are needed to lend visibility and credibility to perception research, and to highlight its importance to the medical community. This is important not just to facilitate the research itself, but also to encourage adoption and implementation of research-based solutions to clinician challenges. Potential models for this network include the National Collaborative on Childhood Obesity Research (NCCOR) and the Alliance for Digital Pathology (ADP). NCCOR is a partnership between federal government agencies (NIH, USDA, and CDC) and the non-profit Robert Wood Johnson Foundation. NCCOR provides infrastructure and resources to promote collaborative research, and supports an outreach program to educate the community on successful collaborations that are fighting childhood obesity. The Alliance for Digital Pathology is a regulatory science initiative that brings together clinicians, researchers, government, and industry to identity key aims to advance digital pathology and provide an infrastructure for collaborative projects.

Outreach efforts at conferences are needed to engage and inform the communities. Symposiums should be held at clinician conferences, such as the ASCP and RSNA, to educate clinicians on how the science of cognition and perception can inform their work, and to highlight research findings that have produced positive changes in clinical practice. Perception researchers should create a model "reading room of the future" at conferences and invite clinicians to different workstations that promote research outcomes. Symposiums and workshops on medical image perception should be held at cognition and perception conferences (e.g., Psychonomic Society, Vision Sciences Society). As a model, consider the outreach efforts conducted by The International Society for Optics and Photonics (SPIE) to educate researchers on the clinician's perspective and challenges, such as organizing demonstrations of clinicians interpreting images to allow researchers to learn how clinicians read.

Clinicians should be given training in fundamental concepts of cognition and perception, as they pertain to diagnostic performance in clinical practice. This training should be included in the noninterpretive skills section of the American Board of Radiology (ABR) Core and Certifying examination. Similar to the educational module for CME credit (see *Enabling Collaborative Transdisciplinary Research* section), fundamental topics should include: classification of visual search errors, development of global processing, attentional mechanisms related to clinical practice, and classic perceptual and interpretive errors. It would also be a good idea to revive the practice of providing training for NIH study sections tasked with reviewing medical image perception research proposals.

Publishing cognition and perception medical image research in medical journals, particularly special issues journals (e.g., human observer performance issues in Journal of Medical Imaging), ensures credibility and visibility among clinicians. However, publishing in main radiology journals is uneven. Research papers, tutorial reviews, and editorials should be placed in prominent journals read by radiologists, pathologists, and other clinicians. Special issues could be commissioned. Potential journals to target include: *Journal of Medical Imaging*, *Archives of Medicine*, *Modern Pathology*, *Journal of Pathology Informatics*.

Ways to Elevate Medical Image Cognition and Perception's Profile Within the Medical Image Community
1. Create a network of invested stakeholders (e.g., clinicians, academia, biomedical informatics, government and regulatory agencies, medical centers, industry) to support an awareness program promoting education, collaboration, and research.
2. Outreach and Roadshows.

- Educate clinicians about cognition and perception.
- Educate cognition and perception researchers about the clinicians perspective.
- Add outreach to the perception lab model.
  - Reading room of the future| | 3. Education Trainings.
- Trainings on cognitive and perceptual fundamentals as "noninterpretive skills".
- Trainings for study sections.| | 4. Publish research in special issues in medical journals to ensure credibility and visibility among clinicians.|

Table: Medical Image Cognition and Perception's Profile {#tbl:profile}

Future goals and strategies to evaluate progress

The overall goal in advancing medical image perception research is to improve patient care by reducing diagnostic errors, improving machine interfaces, and mitigating clinicians' challenges. How will we know if this initiative is bearing fruit? Table ?? lists intermediate goals, metrics, and strategies to evaluate and achieve progress.

We can track the success of outreach efforts by looking at metrics such as the number of funding announcements or the number of new principle investigators recruited into the field. We can also track the impact of medical image perception research on clinical practices (e.g., industry modifications to workstations and AI, decrease in malpractice lawsuits), clinical outcomes, such as reduction in errors, reduction in time clinicians spend per case, and reduction in clinician burn-out rates, and outreach efforts (e.g., grants funded, workshops and perception pop-up labs held at conferences). Ultimately, these clinical outcomes should be modeled to measure the overall improvement in potential lives saved and/or quality of adjusted live years gained. The baseline for the trajectory of the field using the proposed metrics should begin with 2014, the year that NCI's Vision Science Problems in Medical Imaging Workshop was held. We can then compare progress to a counterfactual trajectory, based on extrapolating prior trends, and assess what is needed to change and/or further change the trajectories' slopes.

A match-making resource (see *Enabling Collaborative Transdisciplinary Research* section) will be an instrumental tool for the medical image and cognitive science communities to connect and network for possible collaborative research in whichever capacity they choose. Since, the Think Tank convened, NCI has created a website <<https://cancercontrol.cancer.gov/brp/bbpsb/cognitive-changes/perception.html >> where contributors are asked to list their name, title, affiliation, email, area of expertise or interest, and brief description of a proposed project or potential research contribution. Content is only visible to consenting contributors.

Engaging the broader and higher order cognitive science community, such as human judgement, decision making, and financial decision making, can offer a unique set of skills, expertise, and perspectives for addressing problems faced by clinicians (see *Identifying Research Gaps* section). For example, clinicians are often confronted with classic decision-making problems, (i.e., integrating abundant and various forms of information and making multiple decisions) which have been extensively researched but not in the context of medical imaging. These communities could offer insight to further advance medical imaging research. Symposiums and workshops on medical imaging

and clinicians' issues should be held at broader cognitive science conferences to engage widespread audiences (i.e., Society for Mathematical Psychology, the Society of Medical Decision Making).

Future Goals and Strategies to Evaluate Progress
1. Metrics.

- Track the number of funding announcements, grants submitted, grants funded, workshops and pop-up labs held at conferences, new principle investigators in the field.
- Track clinical practice changes.
  - Industry modifications to workstations that have resulted from cognition and perception research.
  - Reduction in diagnostic errors.
- Quantify the trajectory starting in 2014, what is the counterfactual?
  - What can we do to change the slope?| | 2. NCI's networking website.
- https://cancercontrol.cancer.gov/brp/bbpsb/cognitive-changes/perception.html| | 3. Engage the broader cognitive science community.|

Table: Future Goals {#tbl:future-goals}

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1. We use the term "medical image perception" to cover a wide range of imaging techniques from images of individual cells used in pathology to whole-body radiological images, from glass slides to

3D computer renderings. In addition to detection and diagnosis, medical imaging can also be used to guide surgical interventions. We also extend to term beyond artificially created images; a dermatologist examining your skin, for example, is engaged in a medical image perception task.↩

2. Here we will use the word "clinicians" to refer to anyone tasked with reading a medical image. The typical clinician in this sense will be a radiologist or pathologist, but the term should be understood to include many other specialties such as nuclear medicine or dermatology, as well as non-specialists who read images as part of their practice.↩

3. We are using "perception research" as a shorthand for all the research fields that can contribute to an understanding of the cognitive and perceptual context of medical image perception. This should be understood to encompass cognitive psychology, vision science, cognitive neuroscience, and so forth.↩